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The Plio–Pleistocene demise of the East Carpathian foreland fluvial system and arrival of the paleo-Danube to the Black Sea

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Abstract: This paper studies the Porat Formation (Fm.), which was deposited along the NE margin of the Dacian Basin part of the East Carpathian foreland (ECF) during the Pliocene and Early Pleistocene. We use a review of stratigraphic data in combination with lithofacies and sedimentary architecture analysis to interpret the Porat Fm. as a large sandy alluvial basin infill with an aggradational structure, consisting of cyclic successions of shallow sandy high-energy braided rivers. Aggradation of the Porat Fan was governed by subsidence of the Dacian Basin, along with a northerly supply of water and sediment from the Carpathians. Along the southern margin of the area the fan entered the Reni–Izmail-Trough, which formed the periodically active gateway between the Black Sea and Dacian basins. Along this trough, the Porat Fm. is developed in a different facies, discerned as the Dolynske Member (Mb. 1), which accumulated in the channel of a large river interpreted as the paleo-Danube. According to mammal stratigraphy of the Porat Fm. this continental-scale river had reached the area by the Gelasian to early Calabrian. The Porat alluvial infill indicates a stable water supply from the Carpathians, which explains the ecologically mixed fauna in its deposits: moistened forested alluvial plain-valleys were present between the zonally semi-arid steppe interfluves. The Porat Fm. and the previously studied late Miocene Balta Fm. are key elements for further in-depth study of the terrestrial evolution (tectonic–sedimentary–relief) of the ECF and north-western Black Sea coastal regions.

Keywords: Paratethys, East Carpathian foreland, Pliocene, Quaternary, alluvial deposits.

Introduction

This paper sheds light on the geology of the fluvial Porat Formation (hereafter "Fm."), which accumulated in the border region of Romania, Moldova and Ukraine during the Pliocene–Gelasian–Calabrian (Fig. 1). This area (hereafter "Porat area") occupied a key position between the Black Sea and Dacian basins, which were part of the enormous almost land-locked Paratethys Sea (Rögl 1998; Popov et al. 2004). As it is established in the course of the present study, the south-eastern corner of the Porat area, a trough along the northern margin of the Dobrogea Orogen, sometimes served as a connecting straight between the Black Sea and Dacian basins and at other times it formed a terrestrial barrier. Despite the high level of outcropping, abundance of fossil material and great number of local publications, there is no modern synthesis of the geological development of the Porat area. There are currently a number of competing paleogeographic and sedimentary concepts and local stratigraphic schemes with multiple names for the same stratigraphic units in different locations.

Our research objective was to distinguish and map fluvial formations and their elements for the subsequent reconstruction of the fluvial sedimentation and relief evolution of the study area, in tight correlation with tectonic, climatic and sea-level events. We explored the geology of the Porat area, with a particular emphasis on its rich record of fluvial deposits, most informative among its analogues present along the north-western coastal area of the Black Sea (Matoshko et al. 2009). In this paper we also make an effort to combine and juxtapose the different datasets, approaches and views of various groups of researchers from Romania, Moldova, Ukraine, Russia, Netherlands as well as from some other countries. In our work, we have paid particular attention to the role of tectonic movements as a factor of influence on the reconstructed sedimentary processes.

How large parts of the brackish–marine sedimentary environment of the Paratethys were converted into new land remains a picture painted by rough strokes. Nevertheless, the last study (Matoshko et al. 2016) confirmed that fluvial formations are very informative objects for the comprehension of sedimentation and morphogenesis in the vicinity of the land-sea borderline during basin retreat. During the late Miocene, a large-scale fluvio–deltaic system known as the Balta Formation (Matoshko et al. 2016) developed in the East Carpathian foreland (hereafter ECF). Its progressive progradation was interrupted by a marked transgression at the base of the Pontian

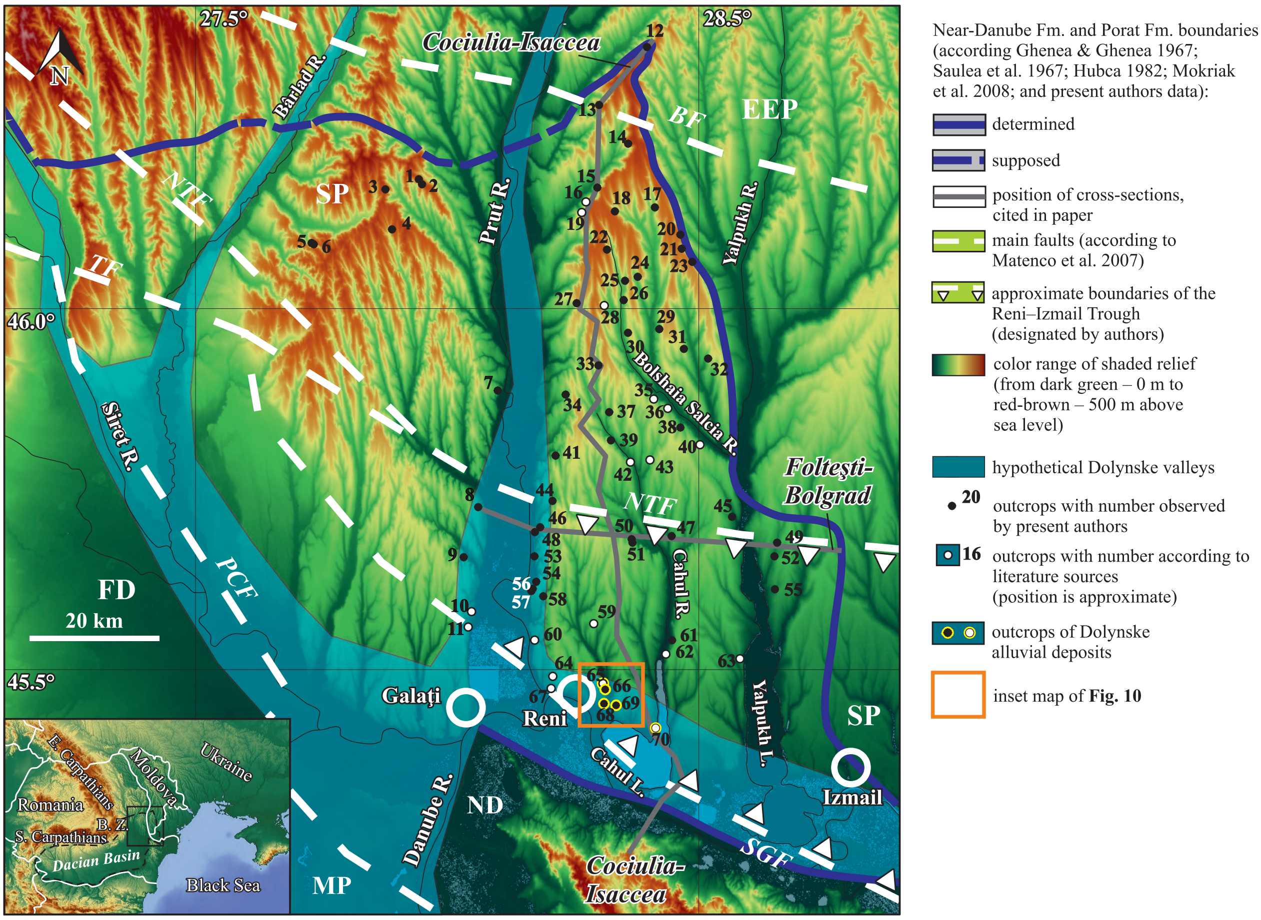

Fig. 1. Location map and map of outcrops used for the study. Names of tectonic units and faults according to Matenco et al. (2007): EEP — East European Platform, SP — Scythian Platform, ND — North Dobrogea, MP — Moesian Platform, FD — Focşani Depression, BF — Bistriţa Fault, NTF — New Trotus Fault, PCF — Peceneaga–Camena Fault; according to Bala et al. (2003): SGF — St. Gheorghe Fault. Outcrop names linking to numbers: 1 — Măluşteni 1; 2 — Tuţcani; 3 — Mânzăteşti; 4 — Bereşti; 5 — Bălăbăneşti 1; 6 — Bălăbăneşti 2; 7 — Slobodzia Oancea; 8 — Folteşti; 9 — Ljidileni 1, 2; 10 — Tuluceşti; 11 — Vanatori; 12 – Cociulia 1; 13 — Lărguţa; 14 — Crăciun; 15 — Ciobalaccia 1; 16 — Ciobalaccia 2; 17 — Chioselia; 18 — Cîşla; 19 — Flocoasa; 20 — Chioselia Mare; 21 — Frumuşica; 22 — Holuboaia-Doina; 23 — Borceag; 24 — Spicoasa; 25 — Tătăreşti 1; 26 — Tătăreşti 2; 27 — Andruşul de Sus; 28 — Luceşti; 29 — Tartaul de Salcie; 30 — Trifestii Noi; 31 — Albota de Jos; 32 — Hîrtop-Balabanu; 33 — Moscovei; 34 — Cahul 2; 35 — Dermengi; 36 — Budăi 1; 37 — Ursoaia; 38 — Budăi 2; 39 — Pelinei; 40 — Musaitu; 41 — Manta; 42 — Vladimirovca; 43 — Gavanoasa; 44 — Colibaşi 1; 45 — Vynogradivka 1; 46 — Colibaşi 2; 47 — Vulcăneşti 1; 48 — Colibaşi-Brînza; 49 — Bolgrad 1; 50 — Vulcăneşti 2; 51 — Vulcăneşti 3; 52 — Bolgrad 3; 53 — Valeni 1; 54 — Valeni 2; 55 — Topolyne; 56 – Valeni–Slobodzia Mare 1; 57 — Valeni–Slobodzia Mare 2; 58 — Valeni–Slobodzia Mare 3, 4; 59 — Cişmichioi 1, 2; 60 — Cislita–Prut; 61 — Etulia Noua 6; 62 — Etulia Noua 2; 63 — Kotlovyna; 64 — Giurgiuleşti 1; 65 — Dolynske 1; 66 — Dolynske 2; 67 — Giurgiuleşti 2 (Ripa Scortselskaia); 68 — Dolynske 3; 69 — Dolynske 4; 70 — Lymanske 1 (see GPS coordinates of the outcrops in Appendix). Inset map: E. — Eastern, S. — Southern, B.Z. — Bend Zone.

regional stage (corresponding to the late Miocene, Messinian). Our current study addresses the subsequent, Porat Stage (Pliocene–Gelasian–Calabrian), for which we discern Early and Late Porat substages in the evolution of the ECF, when the previously widespread Balta system was transformed and alluvial deposits started to accumulate in a number of more localized depocenters, among which the Porat area. This can be considered a transitional stage towards the eventual formation of the familiar cut-and-fill terraced river valleys of the Pleistocene. We furthermore lay an accent on the evolution of the NE margin of the Dacian Basin and its connection directly to the Black Sea during the Pliocene–Gelasian–Calabrian through a detailed study of the fluvial Porat Fm.

Another important question which we address is the age of the first appearance of the Danube in this critical gateway area between the Dacian Basin and the Black Sea.

Estimates for the timing of the arrival of the continental-scale Danube River to the Black Sea are debated and range from the late Miocene (Clauzon et al. 2005) to Pleistocene (Wong et al. 1994). Clauzon et al. (2005) suggested that the Danube arose during the supposed Messinian desiccation of the Dacian Basin and the Black Sea. Andreescu (2009), on the contrary, inferred that the river pierced through the Iron Gates at the western margin of the Dacian Basin about 2.0–1.8 Ma ago, based on an influx of fresh-water molluscs from the Pannonian Basin as well as alluvial deposits in the western part of the Dacian Basin, meaning its arrival to the Black Sea could only have occurred later. According to Olariu et al. (2018), the Danube appeared on the Romanian Black Sea shelf at about 4 Ma, as indicated by an increase in sediment volume above an intra-Dacian erosional surface and a coincident change in the architectural style in the adjacent deepwater fan. The only available dated provenance record from the Black Sea Basin (de Leeuw et al. 2018), indicates that Danube-supplied sediment first arrived sometime between 4 Ma and 1 Ma ago, but does not provide more conclusive age constraints either. A factor that has remained completely under-addressed in in this discussion is the geology of the final gateway of the Danube to the Black Sea, which we address in detail here.

Geological setting

Designation of the Porat Fm. and Dolynske Mb.

The Porat area has a long research history, albeit mostly restricted to publications in Romanian, Ukrainian and Russian. We here build on some recent reviews (Gozhik 2006; Mokriak et al. 2008; Matoshko et al. 2009) that have renewed and restructured the published information on our study area to some extent. Scattered data regarding the Pliocene–Quaternary faunal remains unearthed in this area were first reported during the 19th century. Much later Konstantinova (1967 with reference to Pavlov 1925) suggested naming the sands with gravel and Roussillon fauna near the Prut River the Porat Fm., which referred to the Roman name for the Prut River: "Porata". The formation was further divided into Lower and Upper Porat units.

Meanwhile, Ghenea (1968, 1997) carried out research within the northern part of the Bârlad–Prut interfluve in Romania (Fig. 1), where he encountered deposits with a very similar nature to the Porat deposits on the Moldavian side of the Prut. He described the terrestrial deposits of the Bereşti–Măluşteni Fm. with an Astian large mammal fauna and the Tuluceşti Fm., which has a Villafranchian fauna. These concepts were not modified significantly hitherto, although the subsequent introduction of the BăIăbăneşti Fm., which supposedly overlaps the Bereşti–Măluşteni Fm. and may be correlated with the Tuluceşti Fm. (Ionesi et al. 2005; Enciu & Dumitrică 2008), complicated matters slightly. On the Romanian state geological maps (Ghenea & Ghenea 1967; Saulea et al. 1967) the Bereşti–Măluşteni Fm. was absorbed into the depicted Levantine, whereas the Tuluceşti and BăIăbăneşti formations were attributed to the Early Pleistocene.

Four complexes of alluvial and alluvial–deltaic deposits were distinguished by Gozhik & Chirca (1973) based on collections of freshwater molluscs from borehole cores taken between the Danube, Cahul and Yalpukh lakes (Fig. 1). They attributed these fluvial complexes to the Cimmerian, Kuialnykian and Gurian stages (Middle Zanclean–Calabrian, Fig. 2).

Synthetic sections derived from a number of outcrops along the Bolshaya Salcia and Cahul rivers, as well as two boreholes led Hubca (1982) separate the so-called Carbalia Beds from the Porat Fm. The only argument for separation was a slight difference in fossil assemblages.

Over the course of the Moldavian state geo-environmental survey accomplished in 1994, the Prut-Yalpukh interfluve in Moldova was geologically mapped in detail. The resulting maps depict the Musaitu and Cîşliţa-Prut suites that on the accompanying geological profiles clearly match the Lower Porat unit as defined before by Roşca (1969).

We have here chosen to absorb the numerous Romanian, Moldavian and Ukrainian units (most of them described above) into the Porat Fm. based on their lithological and stratigraphic similarity. On the other hand, we have decided to distinguish the Dolynske Member (hereinafter — Dolynske Mb.), which comprises the upper, southernmost part of the Porat Fm. (Fig. 1). The Dolynske Mb. roughly corresponds to the "Upper Porat" as distinguished by previous authors. The justification for the choice of these units will be made in the following sections of the paper.

Tectonic setting

From the traditional point of view regarding the ancient deep-seated tectonic elements, the Porat area is located on the Paleozoic Scythian Platform and a small marginal part of the Precambrian East European Platform (Fig. 1). To the south and west, it borders the Jurassic–Triassic North Dobrogea Orogen and the Mesozoic–Cenozoic SE Carpathians Orogen with its foredeep. However, it has long been noted that the Miocene tectonic plan in many cases does not match the ancient basement structures and the so-called late Miocene Prutian Trough (at the place of the Porat area) extends eastward from the foredeep not less than 150 km (Rudkevich 1955). Based on findings of numerous tectonic deformations in the terrestrial late Miocene–Pliocene deposits and geomorphological analysis, Bilinkis (1992) suggested that the East European and Scythian platforms in Moldova were re-activated during the Pliocene as a result of the orogenesis in the Carpathians.

During the last decades the post-collisional history of the southern part of the ECF was analysed in terms of the pro-foreland basin, which appeared as a result of isostatic compensation and the resultant flexure in front of the former collisional zone and were filled due to erosional unloading of the orogen (e.g., Sanders et al. 1999; Leever et al. 2006; Matenco et al. 2007). The development of the foreland basin is expressed by asymmetrical subsidence in the late Miocene–Pliocene, which was replaced by uplift and inversion of the basin in the Quaternary. Fielitz & Seghedi (2005) as well as Matenco et al. (2007) extended the foreland basin as far eastwards as the Prut. The results of our previous (Matoshko et al. 2016) and present study indicate the existence of the foreland basin in scale designated by Rudkevich (1955). The part of the presently reviewed area is located in the foreland

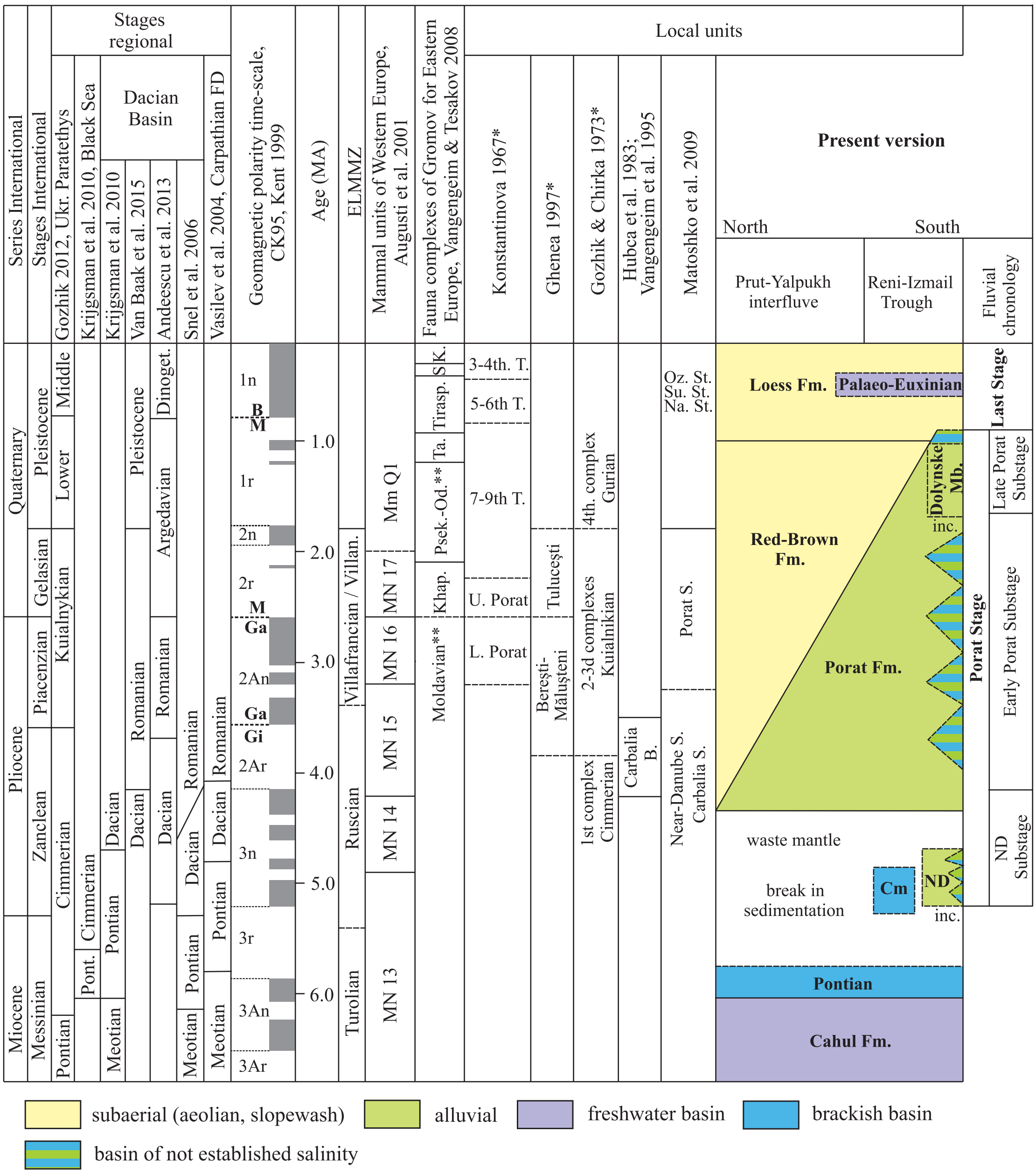

Fig. 2. Correlation table of the Porat Fm. and its probable analogues; by different authors against the background of sedimentary environment evolution. *Local units are put into the table according to their original correlation to ELMMZ; **the regional Moldavian and Odessian complexes of small mammals (Shevchenko 1965) are added by present authors to the Gromov's complexes as that were frequently applied to the fossils of the area in consideration. Abbreviations (columns, left to right): Ukr. — Ukrainian, Dinoget. — Dinogetian, FD — foredeep, B — Brunhes, M — Matuyama, Ga — Gauss, Gi — Gilbert, Villan. — Villanian, ELMMZ — European Land Mammal Mega Zones, Khap. — Khaprovian, Psek.–Od. — Psekupsian–Odessian; Ta. — Tamanian, Tirasp. — Tiraspolian, S–Kh. — Singilian–Khazarian, L. — Lower, U. — Upper, B. — Beds, S. — Series, St. — Suite, Fm. — Formation, Mb. — Member, Villan. — Villanian, Oz. — Ozerne, Su. — Suvorovo, Na. — Nagirne, Cm — Cimmerian, ND — Near-Danube; inc. — incision.

of the so-called Carpathian Bend Zone, which in contrast to the rest of the orogen was in a constructive orogenic phase in the Pliocene–Quaternary (Sanders et al. 1999).

Paleo-environmental setting and climate

Muratov (1964) was one of the first to characterize the landscapes and the climate around the residual basins of the Eastern Paratethys during the Pliocene regional Cimmerian and Kuialnykian stages (Fig. 2). In his opinion, based mostly on paleontology and sedimentary facies, the Cimmerian was the warmest period of the whole Neogene. There were "Subtropical steppes" with red soils and a wide-spread river network surrounded the coasts of the Black Sea and its Dacian bay. The rivers carried out a great amount of iron into the basins, which in some places led to the formation of iron-ore deposits (e.g., the Kerch iron-ore field; Kholodov et al. 2014), or the accumulation of abundant glauconite in transgressive lag deposits (Jorissen et al. 2018). Humidity progressively increased during the Cimmerian and reached a maximum in the Kuialnykian, after which the climate became cooler (Muratov 1964).

The last summary of the landscape–climate features of the south-western part of the East-European Plain was made by Svetlitskaya (1994) based on various paleontological literature data, which included plant macrofossils, pollen, large mammals, small mammals, ostracods, and molluscs. The climate and vegetation of the regional stages of the latest Miocene and Pliocene were characterized as follows.

In the Pontian, the area was covered by a forest–steppe vegetation and the climate was inferred to have been somewhat warmer than now. In the Cimmerian, the area had prevalent broad-leaved forests, which became less widespread at the end of the stage. The early Cimmerian is regarded as the warmest and probably most humid time in the Pliocene, whereas the remainder of the Cimmerian is regarded as fairly dry. In the Kuialnykian, there were mixed conifer and broad-leaved forests, which were replaced by moist steppe vegetation towards the east. Climate was initially rather warm and humid, but a substantial reduction of the forest at the end of the stage indicates cooling and probably aridification. The trend of cooling and moderate aridification continued during the Early Pleistocene (Calabrian), forming the modern steppe landscape of the area.

Despite some general climatic estimates, the characteristics of the individual stages of the Pliocene and Gelasian do not coincide in these studies, which may be due to a different interpretation of the mixed composition of fauna and flora, which belonged to different climatic zones.

Methods

We have conducted an intensive review of previous work, including: the history of the Porat Fm. studies and an essential refinement of the Pliocene–Quaternary stratigraphy. This was followed by our own analyses of the lithofacies and sedimentary architecture of the fluvial formations supplemented by a summary of publications on their mineral and petrographical composition.

For the purpose of mapping and lithofacies analysis we used 70 outcrops (Fig. 1). Many of them are new, while some were known from the literature. Most outcrops are several tens of metres wide and from several up to 30 m high. Thirty of the largest reference outcrops were subjected to thorough facies analysis. The position and altitude of the outcrops were measured using GPS with rough control by topographical maps and satellite images.

Along with these exposures, we used several dozen borehole descriptions from the state archives (DNVP "Geoinform of Ukraine" and State Agency for Geology of the Republic of Moldova). These borehole records were re-interpreted for an analysis of the sedimentary architecture on formation scale with construction of cross-sections.

Results

Review of stratigraphy and age of the Porat Fm. and Dolynske Mb.

Under- and overlying marker beds

In most of the study area, the Porat Fm. erosively overlies mollusc bearing shallow marine sediments that were deposited during the early Pontian (Fig. 2). During our study we registered their direct erosive contact in the Slobodzia Oancea site. They are thus younger than early Pontian. Magnetostratigraphic results from the Dacian Basin and the northern coast of the Black Sea indicate that the base of the early Pontian falls in chron C3An.1n and is consequently 6.1 Ma old, while the top of the early Pontian is 5.8 Ma old (Vasiliev et al. 2004; Krijgsman et al. 2010).

For deposits more recent than the Pontian, there is a difference in stratigraphic terminology between the Dacian Basin and the Black Sea Basin. In the Dacian Basin, the Pontian is overlain by the Dacian (Fig. 2). The Pontian–Dacian boundary is dated at 4.8 Ma (Jorissen et al. 2018). Along the northern coast of the Black Sea, the Pontian is overlain by the Cimmerian. The lowermost Cimmerian forms a reddish condensed interval at the Zheleznyi Rog section on Taman and has a normal polarity (Vasiliev et al. 2004; Krijgsman et al. 2010). It was thus interpreted to have accumulated during the Tvera normal chron with a base at 5.235 Ma (Gradstein et al. 2012). The top of the Pontian could thus be 5.235 Ma or 4.8 Ma old, depending on whether a Black Sea or Dacian Basin stratigraphic framework is chosen.

In the narrow strip south of the New Trotus Fault (Fig. 1) the Porat Fm. overlies shallow, marine-mollusc-bearing early Cimmerian deposits (Mokriak et al. 2008). This indicates that at least part of the Porat Fm. and the complete Dolynske Mb. are younger than early Cimmerian. Along the lowest Danube, the Porat Fm. is underlain by fluvial deposits of the Near Danube Fm. (Matoshko et al. 2009), which was correlated to the Dacian Stage of the Dacian Basin (Gozhik & Chirca 1973) and to the Cimmerian Stage of the Black Sea (Mokriak et al. 2008). In this area, the deposits of the Porat Fm. and Dolynske Mb. are furthermore overlain by estuarine deposits of the Paleo-Euxinian age (Fig. 2). This sets the upper age limit for the fluvial formation.

In many places, a weathering crust had developed on the Pontian before the deposition of the Porat Fm. The top of the Pontian is moreover frequently coloured in bright red. At the contact with the overlying alluvial deposits it is accompanied by red-coloured conglomerate and red-brown lumpy fractured silts-clays interpreted as paleosols (e.g., Ghenea 1968; Roşca 1969; Hubca 1982; Vangengeim et al. 1995; Gozhik 2006). The Porat Fm. is frequently overlain by clays and silts of red, brown, green, grey and blue tints combined in present paper in name "Red-Brown Fm.". This formation occurs widespread on the Scythian Platform and the southern part of the East-European Platform. According to Dodonov et al. (2005) its age range covers the Pliocene and Eopleistocene (Lower Pleistocene in the current scheme). The origin of the Red-Brown Fm. is not clear.

Biostratigraphy

Abundant fossil finds from the Porat alluvial deposits are reported in the local literature. These mainly comprise terrestrial vertebrates and molluscs. However, a thorough analysis of the available information on these fossil finds (without the scrutiny of taxonomy and its knotty history) revealed that for a significant portion the exact place where the fossils were found is not documented, or the fossils were not reinterpreted and classified properly to the modern state of the art. Different researchers commonly worked on different sections and obtained different lists of distinguished species that are impossible to match. In our further consideration we have only taken into account fossils for which the location and classification were properly documented.

It appears that quite a variety of taxons of large mammals with overlapping lineages occur in what could be seen as one vast Pliocene–Calabrian zone (Supplementary Table S1). Others occupy narrower chronological intervals inside the noted zone. A more meticulous look, linking the mammal occurrences with site locations, highlights rejuvenation of mammal ages southwards. The youngest species are found at sites which pertain to the Dolynske Mb. (Fig. 1).

Analysis of the much more numerous remains of small vertebrates and especially the Cricetidae family (Konstantinova 1967; Ali-Zade et al. 1972; Gromov & Polyakov 1977; Shushpanov 1977, 1980; Alexandrova 1989; Vangengeim et al. 1995; Radulescu & Samson 2001; Tesakov 2003, 2004) provides more thorough stratigraphic insight confirming the conclusion made concerning large mammals (Supplementary Table S2). There is an evident up-section younging trend from European Mammal Zones MN 14 to MN 15 for the sites of the northern and central part of the Porat area. There is furthermore a southward younging trend in the fossil assemblages pertaining to the MN 16–17 zones, including those found in the Dolynske Mb. It is mainly on the basis of these fauna variations the previous authors have distinguished the Lower and Upper Porat units.

More than one hundred species of freshwater and euryhaline clams are known from the Porat Fm. (e.g., Konstantinova 1967; Ghenea 1968; Sinegub 1969; Ali-Zade et al. 1972; Gozhik & Chirca 1973; Hubca 1982; Nikiforova et al. 1986; Gozhik 2006; Andreescu et al. 2013) but only some of them have a distinct stratigraphic significance. The lowermost beds of the Porat Fm. especially those directly overlying the Pontian contain various forms of the *Prosodacna* genus very peculiar to the Meotian–Pontian strata of the region. Above these beds, they are not encountered. The lowest part of the Porat Fm. and Tuluceşti Fm. are characterized by gauffering *Margaritifera* of the *Plicatibaphia* genus, transforming to smooth forms upsection (Nikiforova et al. 1986; Andreescu et al. 2013). These are joined by species of the *Psilunio* genus and *Viviparus bifarcinatus* Bielz. passing up to the middle beds of the Porat Fm. As a whole they correlate with the Late Dacian. The species *Psilunio sandbergeri* Neum. emerged in the upper part of the Porat Fm. and also occurs in the Tuluceşti Fm. The upper boundary of the zone with *Viviparus bifarcinatus* coincides with the Gilbert–Gauss Paleomagnetic epochs boundary (Nikiforova et al. 1986).

Paleomagnetic dating

A summary and revision of the magnetostratigraphic study (Hubca et al. 1983; Sadchikova et al. 1983; Alexandrova 1989) of five sections on the right bank of the Bolshaya Salcia valley (Fig. 1), accompanied by small mammal identifications, led Vangengeim et al. (1995) to conclude that the Carbalia beds pertain to the late part of the Gilbert Chron. They have in this case used the MN 15 type mammal fauna as an additional constraint to correlate the polarity pattern of small and isolated sections. The lower boundary of the formation is placed either at the top of, or within the Cochiti subchron (C3n.1n; 4.300–4.187 Ma; Gradstein et al. 2012). The upper boundary of the formation is considered to be near the boundary between the Gilbert and Gauss chrons (3.596 Ma; Gradstein et al. 2012). Given the north–south younging trend in the Porat Fm. demonstrated by the small mammal fauna, sections to the north of those investigated by Vangenheim may be older, whereas those to the south may be younger. In addition, the Bolshaya Salcia sections lay 20–40 m below the local watershed and may be overlain by younger alluvial deposits that are currently unexposed.

Because there are no thick, continuous intervals of the Porat Fm. exposed, paleomagnetic results cannot be correlated to the regional timescale without the aid of mammal or mollusc assemblages. Considering the age of the underlying Pontian and overlying Paleo-Euxinian deposits and the Porat Fm.'s mammal fauna, which ranges from MN14 to MN17 in age, single reversals can be correlated to any part of the magnetic polarity timescale between the middle part of the Gilbert chron to the lower part of the Matuyama chron.

Lithology and lithofacies of the Porat Fm.

We have used lithofacies analysis to provide reliable criteria for the mapping of the Porat Fm. including the Dolynske Mb. and to interpret the sedimentary environment in which they accumulated. Our outcrop examination was integrated with the results of previous studies (Konstantinova 1967; Ali-Zade et al. 1972; Negadaev-Nikonov et al. 1980; Hubca 1982; Hubca et al. 1983). The determination of lithology, sedimentary structures, textures, their spatial relations and some other features is used for identification of lithofacies, which are further combined into characteristic facies associations. A facies association is described here as a stable pattern of distinguishable units (consisting of lithofacies), similarly repeated in a number of sections and bounded by extensive erosional surfaces.

In general, we distinguished two main groups of facies that pertain to alluvial and basin environments respectively. There are two varieties of alluvial associations in the deposits that are traditionally attributed to the Porat Fm. (Table 1). One of them is encountered in the majority of the studied sections within the Prut–Yalpukh interfluve (Fig. 1) and called "Prut–Yalpukh alluvial facies association". The other variety occurs exclusively in several outcrops in a small strip along the lower reaches of the Danube and Prut rivers near Dolynske (Fig. 1). The striking difference in lithofacies and the accompanying difference in occurrence and sand composition, which will be dwelt on below, are the main reasons to distinguish the latter as the "Dolynske alluvial facies association".

Prut–Yalpukh facies association

The Prut–Yalpukh alluvial facies association is represented by a principal lower sand-dominated unit (A) and a less abundant upper mud-dominated unit (B). Its thickness varies from 2 to 8 m. This structure repeats cyclically. The surfaces that separate units of different alluvial cycles are the most continuous surfaces at outcrop, often continuing through the whole exposure. Up to 4–5 alluvial cycles are registered in the highest outcrops (Chioselia Mare, Manta, Colibași 1 and Valeni 2) during this study (Fig. 3). A set of exposures of at least 50 m height on the right slope of the valley Bolshaya Salcia displayed up to 10 such cycles (Hubca 1982; Vangengeim et al. 1995). In places where the Porat Fm. is thicker, more numerous cycles are to be expected. Hubca (1982) wrote about a general coarsening upwards of sands in the upper layers of the Carbalia Beds (upper part of the Porat Fm. in the Prut–Yalpukh interfluve), which is consistent with our observations.

The A unit was traditionally identified in the area of consideration as "sands with gravel" (Figs. 3, 4). Their granulometry varies from very fine to coarse sand. Fine sand prevails. There is no analytical data about sand sorting, but visual estimations indicate a predominance of poor and medium sorting and the absence of fining or coarsening upwards trends. The A unit is dissected by numerous subhorizontal, slightly concave and sometimes incision-like scour surfaces. Among them we distinguish the main intra-unit type of surfaces which separated two varieties of the A unit differing by sedimentary structures and content of coarse material.

The first variety (A1, the most common) is dominated by cross-bedded (trough and planar) and ripple cross-laminated sands. The second variety (A2) contains parallel (or semi-parallel) laminated and trough cross-bedded sands sometimes with a unidirectional dip of the cross-sets (Figs. 3, 4). The second variety also differs by more irregular structure with greater abundance of scours, more frequent soft sediment deformations and usually an increased amount of gravels, which can be up to 2 m thick at the unit base.

Sediments of both the A1 and A2 varieties occur in relatively thin (generally 0.2–2 m) and laterally limited (usually a few meters long) layers or lenses replacing each other in an irregular way. Their cross-bedding sets are 0.1–0.3 m thick on average, reaching in places up to 1 m. The dip of foresets in the A unit shows that paleocurrents varied greatly from west over south to east, with an average southerly direction. The A unit contains scattered gravel clasts and clusters thereof in the coarse sand matrix part of channel lags that line the erosional base of the unit. There is a noticeable increase in gravel clasts in the northern part of the study area and in sites close to the Prut River from Manta (upper part of section) southwards (Fig. 1).

Gravels primarily include carbonate nodules, mud clasts as well as exotic clasts. Mammal bones and mollusc shells (predominantly freshwater) are encountered in many exposures, but clusters of shells (coquina) are found only in the basal horizons of the Colibași–Brînza and Valeni–Slobodzia Mare 1 sites.

Soft sediment deformation is very common, particularly convolute bedding. It is frequently associated with clustered Skolithos-type trace fossils, probably representing escape traces that could made following soft sediment deformation.

The average full thickness of the A unit varies from 4.5 m in the north (e.g., Ciobalaccia, Chioselia Mare, Musaitu, Pelinei) to 3 m in the south (e.g., Colibași 1, Valeni 2, Vulcănești 1–3, Bolgrad 1). The full thickness of the A unit is considered measurable only in cases where it is overlain by the B unit. Where anomalously large thicknesses (6–10 m or more) are mentioned in published sections, these probably represent amalgamated deposits, which include one or two partial alluvial cycles.

Table 1: Characteristic of facies associations.

Facies association		Lithofacies	Thickness	Process interpretation
Prut–Yalpukh	B unit	Sandy silts to clays, either structureless or with parallel lamination. They often show mottling and include carbonate nodules.	0–6 m	Overbank deposition alternating with subaerial exposure.
	A unit	Sands with gravel showing cross-bedding (trough and planar), ripple cross-lamination (cross-bedding sets are 0.1–0.3 m thick on average, reaching in places up to 1 m) and parallel lamination. They are dissected by numerous scour surfaces and often include soft sediment deformation.	3–5 m	Migration of 3–5 m deep channel with moderate to strong variations of discharge.
Dolynske		Sands with bottom gravel, showing cross-bedding, ripple cross-lamination and parallel lamination.	10–20 m	Migration or incision of 10–20 m deep channel with persistent discharge regime.

The B unit lies above unit A with a clear, in places sharp contact. It varies from sandy silts (B1 lithofacies) to clays (B2 lithofacies), either structureless or with parallel lamination, usually finning upwards and is up to 4–6 m thick (Fig. 5a). However, in many cases it is less thick or absent. Its lower contact with the A unit is either sharp, gradational or rarely through alternation. Muds are characterized by greenish-orange mottling and frequent occurrence of patchy or layered carbonate nodules (prevailing in clayey variety). Rarely the top of the B unit consists of a paleosol up to 2 m thick (e.g., Huluboaia-Doina, Musaitu, Vladimirovca, Etulia Noua). Hubca (1982) also suggested frequent occurrence of hydromorphic soils in sections of the Bolshaia Salchia River, but indicated only an elevated organic content as proof. In two cases (Vulcănești 3, Borceag) we observed buried soils with a full profile underlain and overlain by unit A (Fig. 5b). More often the B unit does not reveal significant pedogenic alteration. In this unit there sometimes is some wood detritus, but in general plant residues are very rare in these deposits.

Unit A is usually directly overlain by facies of unit B, or vice versa, in the Porat Fm. However, in some rare cases at the top of the outcrop, unit A facies are overlain by silts and muds, with thinly interbedded fine sands. They are clearly separated by gently inclined-concave surfaces that repeat laterally (Fig. 5a, c).

The relatively thick erosionally based sands of unit A, dominated by current cross-bedding, cross-lamination and often inclusions of the freshwater mollusc shells (including rheophilic ones) are interpreted as channel deposits. The channel deposits of the A1 variety fit classical descriptions (e.g., Miall 2006; Bridge & Demicco 2008) best and imply a relatively even discharge regime with only

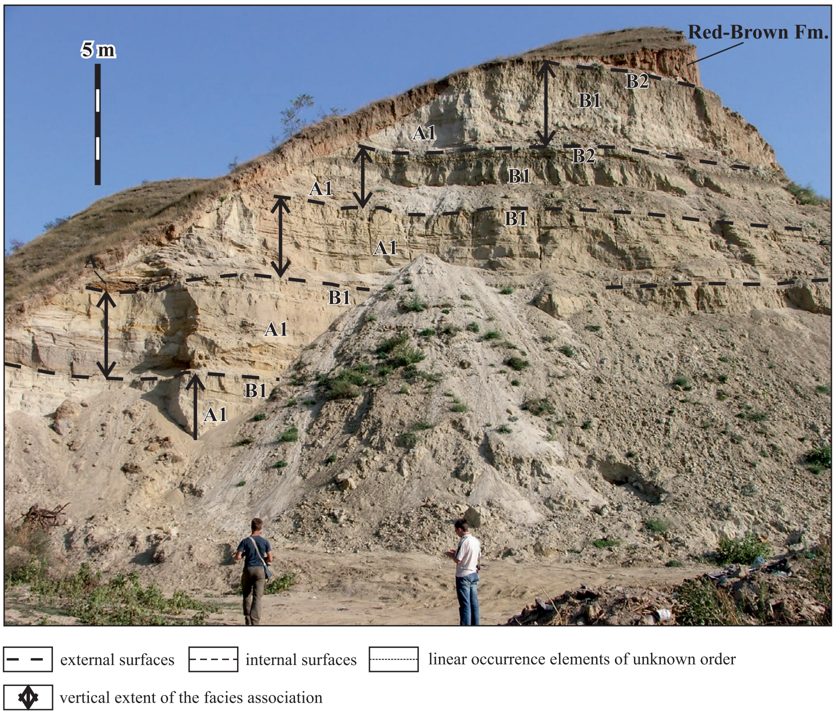

Fig. 3. Porat Fm. Cycles of regularly stacked alluvial facies associations separated by erosional surfaces and overlain by Red-Brown Fm. at the Valeni 2 site. For the lettering of units see the text.

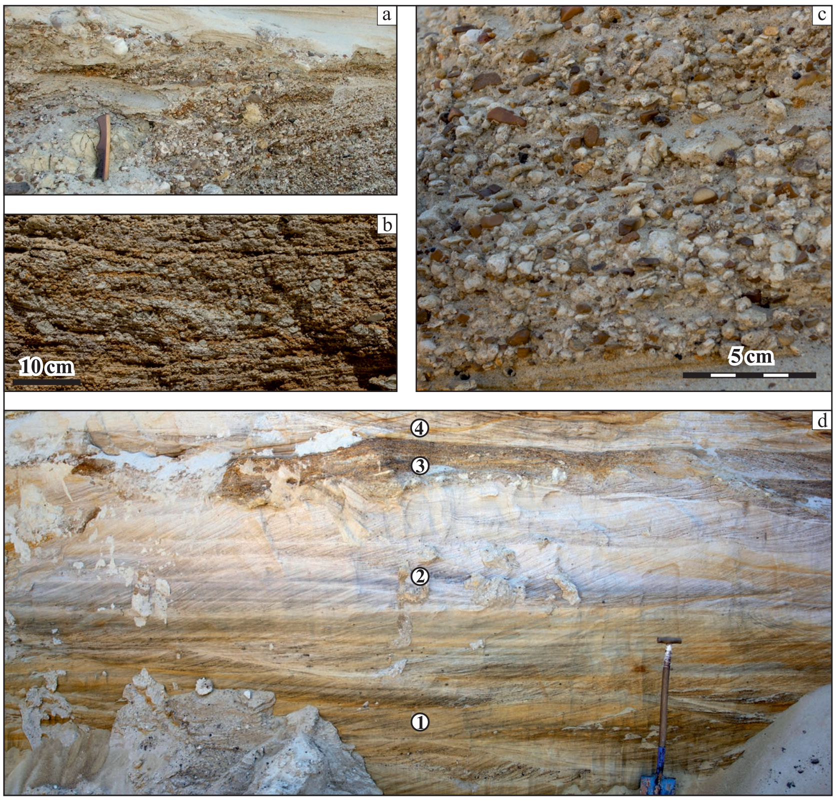

Fig. 4. The Prut–Yalpukh facies association, unit A: **a, b, c** — fragments of the basal horizon containing typical assemblages of mud clasts (greenish), carbonate nodule clasts (whitish) and rock clasts (brown and black cherts, light grey quarts and sandstones): a — dominated by mud and carbonate nodule clasts (Vulcănești 2), b — dominated by mud clasts (Borceag), c — dominated by rock and carbonate nodule clasts (Manta); **d** — upward succession of different lithofacies of unit A: 1 — sands with trough cross-bedding, 2 — sands with planar cross-bedding, 3 — lense of gravelly sands, 4 — sands with sub-parallel lamination (Chioselia Mare). The comb is 14 cm and shovel 1 m long.

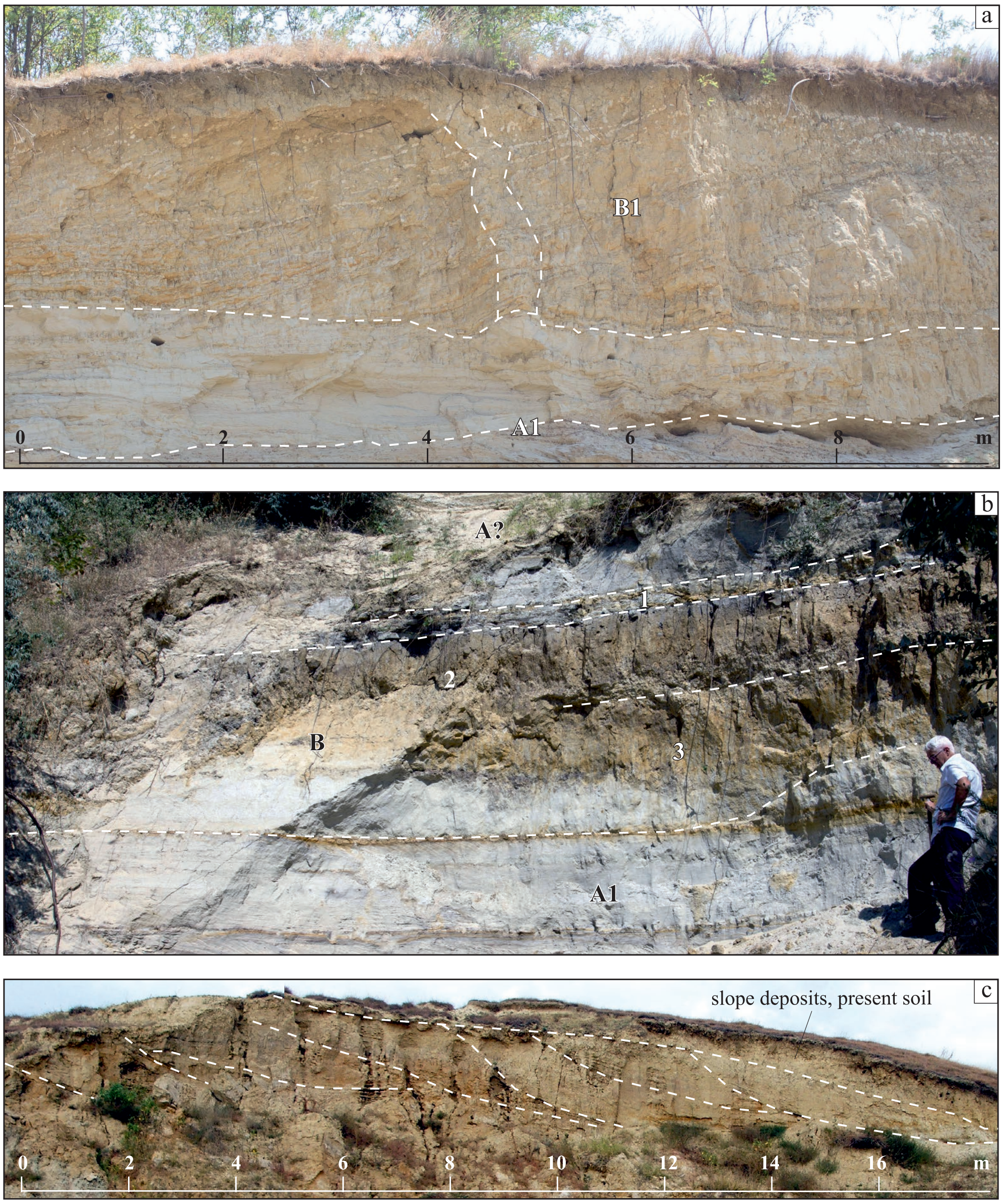

Fig. 5. The Prut–Yalpukh facies association, unit B. **a** — The inclined bedding of lithofacies B1, contrasting with the horizontal bedding of lithofacies A1; in the centre of the picture — syndepositional deformation referred to volcano-like dewatering structure visible from the upward doming of cross sets (Pelinei); **b** — thick automorphic buried soil (1 — horizon of intense weathering, 2 — topsoil with noticeably increase of humus upsection, 3 — subsoil) over B unit occurring between A units (Vulcăneşti 3); **c** — specific concave-inclined stratification of unclear origin, visible in each long exposure (Valeni–Slobodzia Mare 3). For the legend to pictures see Fig. 3, for the lettering of units see the text.

moderate seasonal variations. Whereas a greater abundance of gravel, upper plane bed sedimentary structures, scours and soft sediment deformation in the A2 variety are suggestive of higher energy, pulsed discharge and more rapid deposition. Frequent co-occurrence of the A1 and A2 varieties therefore indicates an alternation of discharge conditions.

The mud-dominated B unit of the Prut–Yalpukh facies, which covers the channel facies of unit A and shows signs of subaerial alteration (mottling, carbonate nodules) accumulated as overbank deposits. Common finning upwards of muds and the absence of sand interlayers suggest that suspension settling prevailed during the final phases of floods. The rare facies with concave-inclined stratification previously encountered in the uppermost floodplain deposits of the Balta Fm. (Matoshko et. al. 2016) were probably formed by alternation of shallow traction currents of variable energy with deposition from suspension. However, the specific shape of these sedimentary structures does not fit any existing concepts (i.e. Thomas et al. 1987) and requires further study.

Dolynske facies association

Apart from the widespread alluvial deposits typical of the Porat Fm., there is a different type of fluvial deposit found only in a few of the southernmost outcrops (Dolynske 1–4, Fig. 1). Similar deposits were also described before from the Giurgiuleşti 2 and Lymanske 1 outcrops (Konstantinova 1967). These alluvial deposits are characterized by a unit (10–20 m thick in exposures) of alternating (0.5–2 m thick) beds of trough cross-bedded, ripple cross-laminated and occasionally parallel laminated sands showing great textural uniformity and containing a significant amount of mica (Fig. 6). The cross-bedding sets are generally 0.3–1.0 m thick with a maximum up to 1.5 m. The cross-bedding dip clearly indicates a predominantly easterly paleocurrent direction. Rather common for these strata are sandstone nodules occurring parallel to the bedding. The cementation suggests high carbonate content. According to (Konstantinova 1967) the basal gravels are occasionally observed and reach 4 m thickness. We distinguish these deposits as channel facies using the same principals concerning A unit of the Prut–Yalpukh facies association. However, unlike the cyclically built Prut–Yalpukh association, the deposits of the Dolynske Mb., distributed along the lowermost Danube, are uninterrupted.

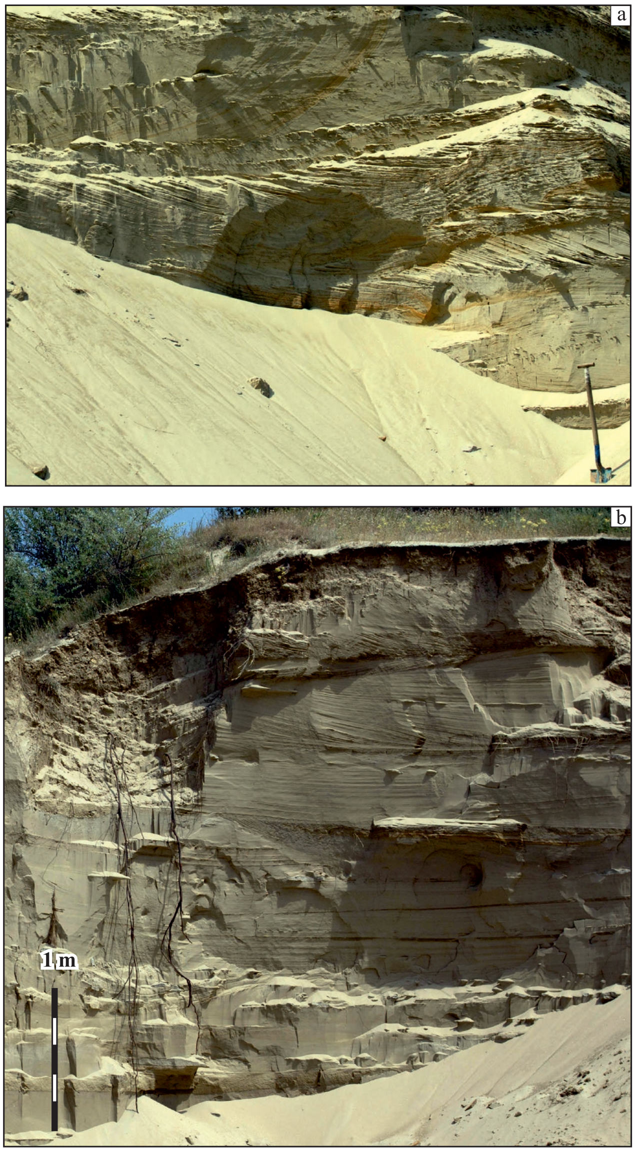

Fig. 6. The Dolynske facies association. Alluvial deposits characterized by monotonous metre-scale interfingering of horizontal laminated and cross-bedded mica-rich sand: **a** — with predominance of cross-bedding (Dolynske 2); **b** — with predominance of horizontal lamination with numerous sandstone nodules (Dolynske 4). The shovel is 1 m long.

Basin facies

In some southern outcrops along the lower Prut and along the lowermost Danube (Valeni–Slobodzia Mare 2, Dolynske 1, 3) the sandy alluvial deposits are overlain by thick planar-bedded mudstones that are clearly different from floodplain deposits. At the Dolynske sites, they consist of thick and uniform, thinly laminated clays (Konstantinova 1967). Lamination is either plane parallel or wavy. The transition from the underlying sands of the Dolynske alluvial facies association occurs through micaceous silts with the same sedimentary structures and nodules that are characteristic for the sands. The total thickness of the exposed muds reaches 19 m. At the site Valeni –Slobodzia Mare 2, very similar muds overlie alluvial deposits of the Porat Fm. (Fig. 7). The transitional interval is marked by micaceous fine sands with nearly unidirectional ripple cross lamination indicative of northerly paleo-flow, possibly deposited in an estuarine environment. The basal mudstones contain some minor burrows and some sporadic freshwater ostracods (pers. comm. M. Stoica). We interpret these muds to have been deposited in a calm lacustrine environment below the wave base.

According to Rengarten & Konstantinova (1965), characteristic drapes of coal detritus and mica particles oriented in one direction line the horizontal lamination of well sorted sands, silts and clays. They also noted that some of the bluish-grey uniform structureless clays contain rare foraminifers and grains of authigenic glauconite (0.05–0.1 mm). Rengarten & Konstantinova (1965) infer from these observations that the muds accumulated in a brackish basinal environment.

Drilling in the southern part of the research area revealed that there is a thick interval with muds (Gozhik & Chirca 1973; Gozhik 2006), similar to those exposed at outcrop near Dolynske, Valeni and Slobodzia Mare. However, in line with our own observations and contrary to those of Rengarten and Konstantinova, the molluscs from these deep horizons indicate that they have accumulated in a freshwater environment.

Mineral and petrographic composition of the Porat Fm.

Sands

According to Hubca (1982) the sands of the Carbalia Beds (here seen as the lower and middle parts of the Porat Fm.) are quartz-rich (70–75 %), but with a noticeable content of feldspars (up to 10–11 %) and fragments of cherty rocks (10–16 %). The key assemblage of heavy minerals of the lower part of the Porat Fm. (Carbalia, Musaitu, Tătăreşti, Cahul and Etulia

Nouă) in the fraction 0.25–0.01 mm is very stable: garnet (30–50 %), ilmenite (10–26 %) and leucoxene (10–25 %), with a total percentage more than 50 %. The heavy fraction (0.1–0.01 mm) of the Porat Fm. at Cîşliţa–Prut also consists of 50–60 % of opaque minerals and garnet (Rengarten & Konstantinova 1965). In BăIăbăneşti, opaque minerals comprise up to 75 % of the heavy mineral fraction, while garnet takes the second place (Ghenea 1968). In some localities near the base of the Porat Fm. at the contact with the Pontian, an increased content of hornblende, andesine, volcanic glass and some other minerals occurs. This has been considered to be due to volcanic activity (Hubca 1982).

Apart from the presence of a significant proportion of opaque minerals, the here observed garnet abundance is common in the EC foreland deposits. For example, it was noted in the late Miocene Balta Fm. (Matoshko et al. 2016) as well as for the sand of the present-day Prut and Dniester Rivers (de Leeuw et al. 2018, Supplementary material).

The proportion of heavy minerals in the fraction 0.1–0.01 mm of the sands of the Dolynske Mb. varies from fractions of a percent (probably lacustrine deposits) up to 16–18 % (probably channel lag deposits) (Rengarten & Konstantinova 1965). There is a striking predominance of hornblende and epidote (26–48 % both), alongside opaque minerals (27–34 %) (Rengarten & Konstantinova 1965). In addition, sand of the Dolynske Mb. (Giurgiuleşti 2, Dolynske and Limanske sites, Fig. 1) is rather micaceous, including dark coloured mica of the biotite group and colourless mica. This has previously been reported by Rengarten & Konstantinova (1965) and Hubca (1982), and was confirmed for the Dolynske and the lower part of the other outcrops in the course of the present study. The detrital fraction of the sand is polymict and includes quartz, feldspar, fragments of flints and schists.

Gravels

Gravel is a permanent intrinsic component of the Porat Fm. sandy facies. The gravels contain local and reworked far-transported material. The first group consists of rounded clay balls, clayey–silty and carbonated nodules. The second group is represented by relatively hard rocks such as limestones, rare sandstones and the so-called "Carpathian Pebbles". In most cases the mud clasts prevail.

The "Carpathian Pebbles" are a distinctive far-transported feature for the whole Porat Fm. These "pebbles" are small slightly rounded fragments and grains (1–2 mm to 3–5 cm intercept) of brown-red, yellowish jaspers, flints and silicified claystones. The features of these pebbles have been elucidated in detail by Matoshko et al. (2016). Their primary sources have not been accurately established. A secondary source for these pebbles in the Porat Fm. is the late Miocene Balta Fm. to the north, part of which was being eroded during the Pliocene and Pleistocene.

Sands with a high content of gravel represented by menilites, sandstones and some other fragments occur in the BăIăbăneşti and Tuluceşti sites (Ghenea 1968). Our observations near Bereşti and Măluşteni have shown that the menilites reported in the Romanian literature and the "Carpathian Pebbles" reported in the Ukrainian literature are the same type of rock. According to Ghenea (1968), at some outcrops of the BăIăbăneşti Fm. (which we consider part of the Porat Fm. here), the percentage of menilites is 35–37 %, quartz 27–30 %, sandstone 29–30 %, and quartzite 4 % in the fraction of gravel larger than 1 cm.

Fig. 7. The basin (probably lacustrine) facies of the Porat Fm., horizontally laminated uniform silts with unidirectional ripples at the base, lying with sharp contact on the A unit of the Prut–Yalpukh facies association (Valeni–Slobodzia Mare 2). For the lettering of units see the text.

Gravelly channel lags of the Dolynske Mb. were only infrequently observed during the course of this study, because the lower parts of the corresponding outcrops are at present poorly exposed. These lags include the "Carpathian Pebbles". Rengarten & Konstantinova (1965) mention that there are in addition fragments of granites, metamorphic schists, and quartzites associated with the micaceous sands. These authors attribute this to a direct influence of the adjacent North Dobrogea Orogen. Except for mud balls (Fig. 4a), most other clasts do not exceed 2–3 cm across and large pebbles were encountered in two locations.

Muds

While the muds of the Porat Fm. are often called clays in the literature (e.g., Rengarten & Konstantinova 1965), detailed descriptions as well as our own field data reveal that most of them are silts with variable admixtures of clay or sand. Real clays of the Porat Fm. consist of 91.3 % of fraction less than 0.01 mm, 8.3 % (fraction: 0.1–0.01 mm) and 0.4 % of fraction more than 0.1 mm (Zheru 1978). The Porat clays comprise a hydromica–montmorillonite assemblage with a noticeable admixture of mixed-layer minerals (Hubca 1982; Mokriak et al. 2008). The authigenic components in the muds are carbonates, iron and manganese. An increased content of calcite and dolomite in nodules and in dispersed form (up to 5 %) is attributed to the lacustrine origin of the muds by Hubca (1982). In some places, carbonates furthermore cement sandy and gravelly channel deposits. A somewhat different description of the lacustrine deposits near Dolynske was cited by Rengarten & Konstantinova (1965) and briefly in the section “Basin Facies”.

Sedimentary architecture of the Porat Fm.

The Porat Fm. within the SE Carpathian foreland

Abundant archive geological survey data from the Ukrainian and Moldavian territories, in particular geological maps and borehole descriptions, were used to supplement the information obtained from outcrops. This provides a more complete picture of the general sedimentary architecture of the Porat Fm., which we synthesize with the stratigraphic, lithofacial and lithological data provided above, as well as some geomorphological observations.

According to geological maps (Ghenea & Ghenea 1967; Mokriak et al. 2008), as well as our own data, the Porat Fm. has a triangular shape in plan, with its top at Cociulia, a site located near the supposed northern boundary of the Pontian shallow marine deposits (Fig. 1). The thickness of the Porat Fm. within the studied Bârlad–Prut–Yalpukh interfluves varies from 40 to 70 m (except the Reni–Izmail trough, see below); its average basal slope in the south-south-east direction is about 0.0028 (0.160). The formation wedges out to the north and east.

Pontian shallow marine deposits underlie the Porat Fm. almost throughout the area and are inclined slightly to the S and SSW. The Pontian–Porat contact also dips in this direction (Fig. 8). The contact has the character of a terrestrial break in deposition as indicated by a weathering layer at the top of the Pontian rocks in several outcrops (Hubca 1982; Vangengeim et al. 1995). In other places there is no obvious evidence of protracted exposure before deposition of the Porat Fm. In many places the Porat Fm. is covered by the Red-Brown and Loess formations. Within the Prut–Yalpukh interfluve these are up to 58 m thick, decreasing to the east and towards the modern valleys. Along its south-western boundary, the Porat Fm. disappears into the subsurface and is overlain by younger Pleistocene–Holocene strata.

Along the triangle’s north-west corner, somewhere in the Siret–Bărlad interfluve, the Porat Fm. is supposedly laterally replaced by Dacian age littoral to delta-front deposits (Jorissen et al. 2018), Romanian age fluvial deposits (van Baak et al. 2015) and Early Pleistocene (Calabrian) alluvial fan conglomerates of the Cândeşti Fm. (Andreescu et al. 2013). This western lateral contact was not observed in the field, but should exist considering the stratigraphic position of the Porat Fm.

A number of small-scale rootless deformations (folds and faults with amplitude up to 20–30 m) of non-sedimentary nature were distinguished within the Prut–Yalpukh interfluve in the Pontian rocks and the Porat Fm. in the walls of gullies and in borehole sections by Bilinkis (1992). This observation was confirmed during the present study. There are also several examples of disjunctive deformations in the Pliocene–Quaternary strata of the Bârlad–Prut interfluve (Matenco et al. 2007).

The Porat Fm. in the Reni–Izmail Trough

For the current study, the most interesting boundary of the Porat Fm. is situated in the southeast, where the formation enters the late Miocene–Pliocene Reni–Izmail Trough (introduced by present authors). This trough is located between two main faults: the New Trotus and St. George faults (Fig. 1). It is formed by a set of successive normal faults, which were active during and after the deposition of the Porat Fm. (Fig. 8). The trough evidently tapers downwards on the Dobrogea side. Its southern flank is represented by epimetamorphosed Precambrian strata and sedimentary formations of Paleozoic and Mesozoic age, while the northern flank is formed by late Miocene (Sarmatian, Meotian and Pontian) deposits. The base of the formation, as well as the underlying brackish-marine formations clearly step down across these faults.

To the north of the New Trotus Fault, the Porat Fm. overlies Pontian shallow-marine deposits (Fig. 8). South of the New Trotus Fault, and so inside the trough, the Porat Fm. overlies Cimmerian (Early Pliocene) shallow marine sediments (Mokriak et al. 2008). The Porat Fm. here includes thicker mud intervals. In the deepest part of the trough the Porat Fm. (80 m thick) lies on the Cimmerian age fluvial Near Danube Fm. (Matoshko et al. 2009). The base of the Porat Fm. is there located lower than observed further north, outside of the trough, but its position is shown at different altitudes in borehole descriptions and cross-sections (Gozhik & Chirca 1973; Gozhik 2006; Matoshko et al. 2009).

The Near Danube and Porat formations both consist of sands and gravels and interfinger with muds containing brackish and freshwater mollusc fauna (Gozhik & Chirca 1973; Mokriak et al. 2008). Towards the Black Sea, within the Danube Delta, some boreholes found Levantine fauna at a depth of 68–100 m (Chirca 1969, with reference to Litianu et al. 1963). This could indicate that the observed trough and Porat Fm. continue into that area.

The Dolynske Mb. in the Reni–Izmail Trough

The Reni–Izmail Trough is also noteworthy for the appearance of the Dolynske Mb. The Dolynske Mb. is up to 40 m thick, occurring alongside the adjacent Prut–Yalpukh type deposits of the Porat Fm. and overlying Cimmerian age clays (Figs. 8, 9). Archive data as well as literature (Gozhik 2006; Matoshko et al. 2009) show that its base lies from 5 m above sea level to 40 m below sea level on the differently lowered blocks of the Reni–Izmail Trough. At its northern margin it is located somewhat lower than the base of the directly adjacent Porat deposits (Fig. 9). In the axial part of the Reni–Izmail Trough at the south-western tip of the Yalpukh Lake, the Dolynske Mb. directly overlies older deposits of the Porat Fm. The contact is located at 40 m below sea level and lined

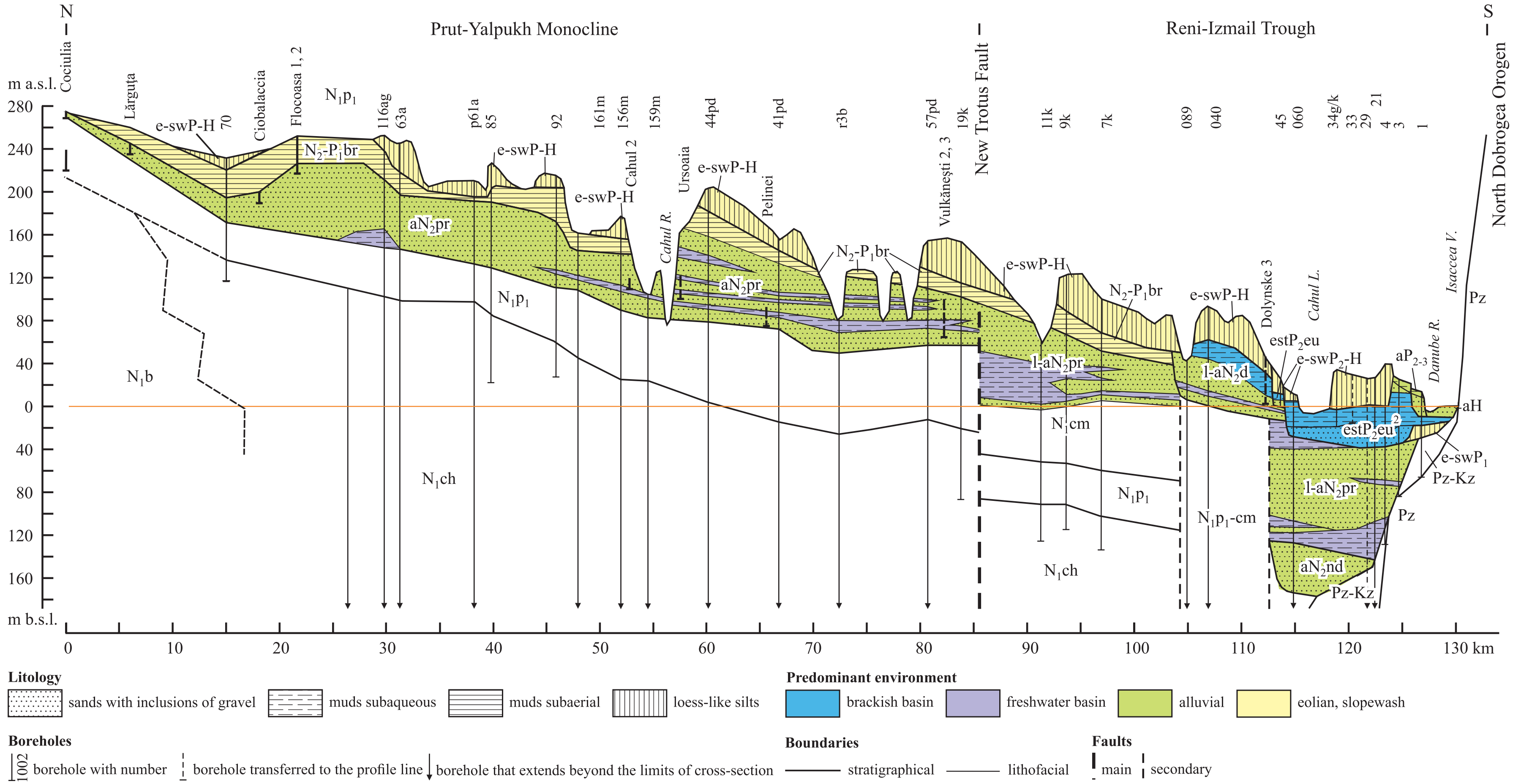

Fig. 8. Geological cross-section Cociullia–Isaccea based on materials of DNVP "Geoinform of Ukraine" and State Agency for Geology of the Republic of Moldova (with small reinterpretation), Sinegub (1969), Bilinkis et al. (1976), and data of present study. Global units: H — Holocene; P — Pleistocene, P2–3 — Middle–Upper Pleistocene; P2 — Middle Pleistocene, P1 — Lower Pleistocene, N2 — Pliocene, N1 — Miocene, Pz–Kz — Paleozoic–Cenozoic, Pz — Paleozoic. Local units:; eu — Paleo-Euxinian Fm., rb — Red-Brown Fm., pr — Porat Fm., d — Dolynske Mb., nd — Near-Danube Fm., cm — Cimmerian, b — Balta Fm., ch — Cahul Fm., p1 — lower Pontian, p1-km — lower Pontian–Cimmerian undifferentiated, a — alluvial, l-a — lacustrine-alluvial, est — estuarine, e-sw — eolian-slopewash. Location of the cross-section see in Fig. 1.

by a 2–4 m thick layer of gravel. The deposits of the Dolynske Mb. are traced by single borehole sections to Izmail and from Izmail 70 km further eastwards (mapped by Cherednichenko et al. 1985) up to the spit of the Sasyk Liman (Palatnaia 1991; Gozhik 2006) and very probably grade laterally into similarly aged deposits of the Dniester valley.

The deposits of the Dolynske Mb. are overlain by basin muds (Fig. 9). These basinal deposits are 8–10 m thick and have their base at roughly 30 m above sea level. The basinal deposits on top of the Porat Fm. are in turn overlain by clays and silts of the Red-Brown and Loess formations while the basinal deposits above the Dolynske Mb. are almost only covered by a loess blanket.

The geological survey maps (archive data) demonstrate that the youngest Pliocene (late Gelasian–Calabrian in our interpretation) alluvial deposits (probably an age equivalent to the Dolynske Mb.), occur on both banks of the modern Cahul and Yalpukh estuaries, with a marked exposure near Vinogradivka. In this connection it is very likely that Porat deposits with Prut–Yalpukh facies association of a similar age to the Dolynske Mb. stretch along the banks of the Lower Prut along a narrow strip (Fig. 1). The alluvial deposits in outcrops Colibași–Brînza, Valeni and further south to Giurgiuleşti are not only associated with younger fauna and the presence of coarser material (see above), but it also occurs in the same visual narrow altitude interval as exposures near Dolynske (up to 25–30 m), being overlain only by loesses or by thin clays of the Red-Brown Fm. (Valeni 2).

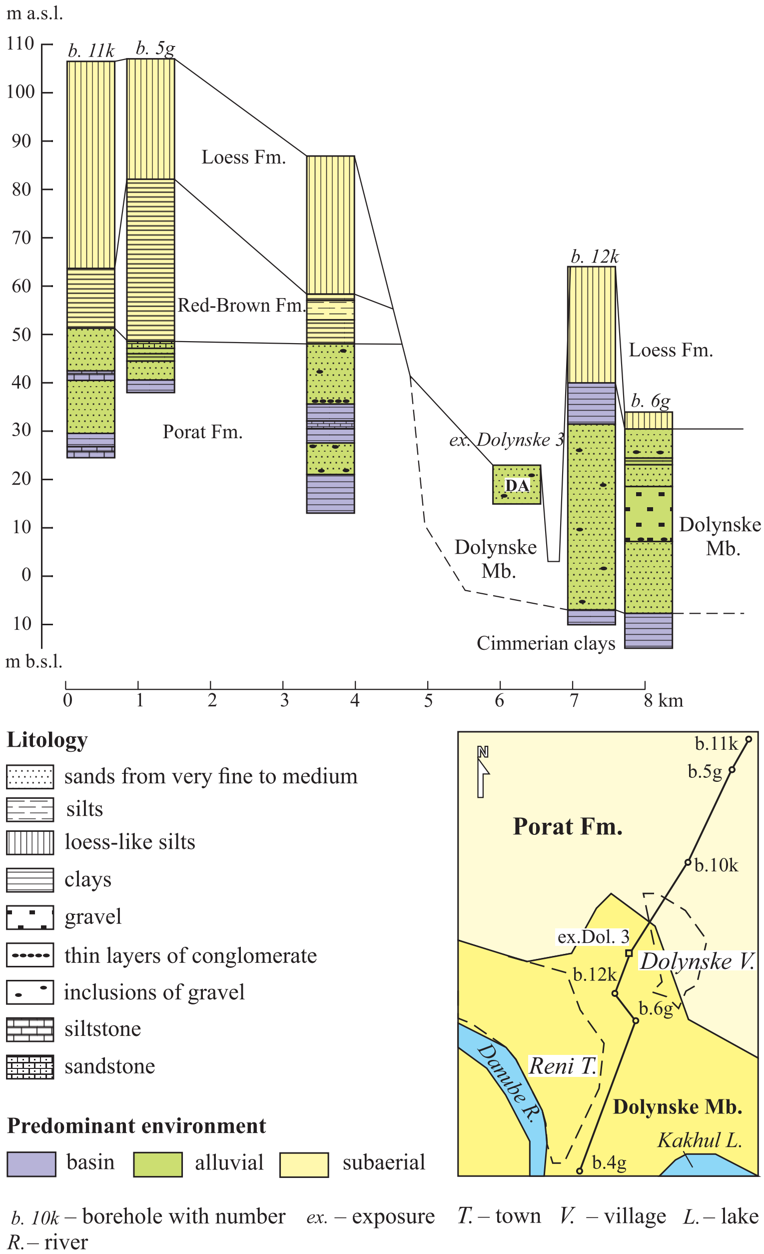

Fig. 9. Geological cross-sections through the alluvial Dolynske Mb. and its correlation with the rest of the Porat Fm. near Reni, based on materials of the DNVP "Geoinform of Ukraine" and observed exposures. Sedimentary environments are according to our interpretation. DA — Dolynske alluvial facies association, characterized at exposures. See position of the inset map in Fig. 1.

Pliocene–Pleistocene river terraces

Konstantinova (1967) suggested a staircase-type stratigraphy in the valley of the Prut River, with ten terraces deposited by the ancient Prut River. The Upper Porat Unit, bearing the youngest mammal fossils, was interpreted as the uppermost river terrace, inset into the Lower Porat unit represented by a thick package of aggradational alluvial deposits. The distinction of the terraces was based on fauna (see above), but not on any analysis of the geomorphology. Nevertheless, this concept was apprehended by some researchers (Sinegub 1969; Bukatchuk et al. 1983), whereas Chirca (1969) concluded that there were no reliable reasons for the identification of at least the 8th, 7th and 6th terraces.

According to our own paleo-geomorphological interpretation, the top of the Porat Fm. formed a vast alluvial plain into which the Dolynske Valley was incised. The Porat Fm. and its Dolynske Mb. were then buried under the Red-Brown and Loess formations. At present all of them form a common lowland surface that gradually descends in a southward direction. Along the lowest reaches of the valleys of the Danube, Siret and Prut, there are one or two Middle–Late Pleistocene and Holocene well-expressed river and estuarine terraces above the floodplain at 6–15 m above sea level as well as a marine terrace with a rich Old Euxinian, Middle Pleistocene mollusc fauna at 25–35 m above sea level (Saulea et al. 1967; Negadaev-Nikonov et al. 1980; Bukatchuk et al. 1983). Above the Old Euxinian terrace, there are no levels resembling terraces in the modern surface near the main rivers. This can be explained particularly by intensive post-Porat erosion and plunging of the Pleistocene alluvial deposits below sea level, which was revealed in other valleys of the Black Sea north-western coast (Matoshko et al. 2009).

Discussion

Sedimentary environment

The rivers of the Porat Fm.

There are several features of the Prut–Yalpukh alluvial facies association (see above) which we consider key for our reconstruction of the rivers that deposited the Porat Fm. These are:

- the sand with gravel composition of the channel facies;
- the fractional lenticular-layered irregular structure of the channel units;
- the abundance of intra-unit incisions in channel deposits;
- the absence of vertical trends in granulometry of the channel deposits;
- the relatively small thickness of the cross-bedding series;
- the sharp contact between channel and floodplain facies;
- the simple vertical structure of the floodplain unit, including one-two varieties;
- the almost complete lack of abandoned channel facies.

In combination, these features indicate a characteristic sandy high-energy braided river (type "D" in the classification of Rosgen 1994). It is supposed that the braided system of channels (braided belt) was active during fluvial seasons or flood episodes accompanied by frequent shifts of the river branches. The maximum bankfull channel depth could be estimated based on the thickness of the channel deposits (Bridge 2003). This suggests on average 3–5 m deep channels. Their width was, according to width/depth ratio > 40 for channels of type "D" (Rosgen 1994), about one to two hundred metres and they had a medium slope. The shape of the channels resembled a shallow trough with gentle flanks. The abundance of dewatering structures suggests high rates of deposition.

The alluvial cycle consisted of channel erosion, fast channel infill followed by rapid covering by floodplain deposits. Flooding of the river plain alternated with subaerial exposure as indicated by soils, reddish muds, carbonate nodules, etc.

General features of the Porat Fm. sedimentation

We interpret the deposits of the Porat Fm. to have been deposited by a wide braided belt with numerous intertwined equal branches. This is confirmed by the observed facies associations, which are indicative of very stable channel conditions throughout the area and through time, as well as the preservation of downstream discharge. With the lapse of time, the braided belt wandered radially over the coastal plain, around the main south-south-west axial direction. Within the study area, we did not see any replacement of alluvial deposits by deltaic facies, which means that sea-ward progradation of the fluvial system was strongly sediment supply-driven.

The vertically stacked alluvial cycles, which repeat throughout the whole Porat Fm., provide evidence of continuous (up to 2 Ma) repetition of the environment of the elementary cycle described above. The steady aggradational trend caused reduction or full scour of the floodplain units as well as part of the channel units, which is common for the aggradational fluvial systems of the East European Plain (Matoshko et al. 2004). This also indicates that sediment supply was equal to, or larger than the local rate of creation of accommodation space. Sand and gravel compositions indicate that the Carpathians and the Balta Fm. provided much of the sediment that accumulated in the Porat river basin. There was also some influence from local sources: the Pontian–Cimmerian strata underneath the Porat Fm. The role of this source reduced through time due to aggradation of the alluvial deposits.

The wandering and seaward progradation of the Porat fluvial system as well as aggradation of the alluvial strata resulted in the particular geometry of the sedimentary body of the Porat Fm., which resembles a flattened cone with the top at the margin of the sedimentary Dacian Basin. This shape satisfies one of the main features of "alluvial fan" in definition of Miall (2000). However, according to our facies interpretation, the Porat River did not diverge into radiating distributaries along its course (second feature in this definition). It therefore cannot be strictly referred to the so-called "fluvial distributary system". Without delving into the unsettled issue of terminology associated with fan-shaped alluvial bodies (e.g., Miall 2000; Nichols & Fisher 2007), we decided to use a neutral term and designate the Porat Fm. as an alluvial basin infill.

The river of the Dolynske Mb.

A rather different sedimentary environment was responsible for the deposition of the Dolynske Mb. The large thickness of its single river channel deposit (10–20 m), with cross-bedding sets of up to 1.5 m, is indicative of a really large and powerful river (much more powerful than the distributary streams of the Prut–Yalpukh type) with a persistent character of high discharge and a very high input of bedload. This river could be referred to "entrenched (gully), step/pool and low width/depth ratio on moderate gradient rivers of the type G" (Rosgen 1994). Near Dolynske it cut a valley about 20 km wide and filled it with a thick channel deposit, which we call the "Dolynske valley infill". In contrast with the rest of the Porat Fm. it was a one-time, rather than cyclical process.

The Dolynske Mb., moreover, has a very different sand composition from the rest of the Porat Fm. and we accordingly infer a different provenance. The heavy mineral assemblage of the Dolynske Mb. (hornblende–epidote, opaque minerals) is similar to that of the present-day Danube and to those of rivers in the western Dacian Basin, which are also rich in epidote and have a comparatively small garnet component (de Leeuw et al. 2018). Epidote is, on the contrary, very scarce in the sediments of the Balta and Porat formations that were sourced from the Outer Carpathians, while these sediments contain a very predominant garnet component. We interpret the Dolynske Mb. as a reflection of the appearance of the Danube along the southern margin of our study area at the beginning of the Late Porat stage.

Probable basin environment

The scant information provided here about the basin facies still suggests the periodic appearance of a lacustrine environment in the near-Danube area and especially in the Reni–Izmail Trough prior, during and after accumulation of the Porat Fm. (Fig. 2). The muds overlying the alluvial deposits of the Porat Fm. and Dolynske Mb. indicate the final episodes of basin deposition in that area, in combination with a steady input of suspended load. The basin was a predominantly freshwater environment with possible phases of salinization. This is not surprising considering that the Black Sea was a lake during most of the Pleistocene (Ross 1978; Krijgsman et al. 2019). It is important to underline that the fluvial facies of the Porat Fm. are abruptly replaced by basinal mudstones, without deposition of intervening deltaic facies.

Comparison with other fluvial series along the northern Black Sea coast

The Porat Fm., including its Dolynske Mb., is not an exceptional phenomenon along the northern coastal plains of the Black Sea and Sea of Azov. Earlier Konstantinova (1967), Tchepalyga (1967), Bukatchuk et al. (1983), and Matoshko et al. (2009) correlated it with other fluvial formations. These include the Lower Dniester terraces (Fîrlădeni, Hagimus and Kitskany, or some of them) and the ancient alluvial deposits near the Dniester Liman, as well as the Kuchurgan Beds and Kuialnykian Series. All of these were deposited in the same chronological interval. Most of them are associated with powerful rivers, the precursors of the Dniester, Southern Buh and Dnieper. These fluvial formations embrace vast areas, have a comparable thickness and aggradational structure in their distal seaside part, as well as some of them also having a fan shape. Thus, their origin is due to a common regional cause or causes such as tectonics, evolution of the associated basins, landscape and climate.

Tectonics as an important factor in fluvial development

From a tectonic point of view, the subsidence in the Dacian Basin, with its main depocenter in the Focsani Depression (Necea et al. 2005; Leever et al. 2006; Matenco et al. 2007; Jipa & Olariu 2009), generated the accommodation space for the Porat Fm. During the late Zanclean, Piacensian and early Gelasian, the subsidence rate of the basin was in close balance with a weak uplift of the river drainage area to the north of the basin (i.e. in the ECF). The fringe zone between the basin and the uplifting area gradually shifted to the S and SSW. The local rate of subsidence was in balance with or smaller than sediment supply from the Outer Carpathians and the terrestrial plains upstream of the Porat area, leading to aggradation of the alluvial cycles. The lack of deltaic facies fundamentally distinguishes the Porat Fm. from the prograding system of the Balta Fm., which is characterized by a full set of facies — from typically alluvial through deltaic to basin ones (Matoshko et al. 2016). During the Porat Stage of deposition, deltas were likely located just beyond the southern margin of our study area, namely in the subsurface along the retreated northern margin of the Dacian Basin.

The incision that cut the valley in which the Dolynske Mb. was deposited could have been stimulated by a slowdown of the subsidence, but also by changes in water level in the basin (see below). Subsidence resumed at its previous rate during the Calabrian which coincided with the deposition of the Dolynske Mb. Finally, the post-Dolynske incision (second half of the Calabrian) may have been aided by cessation of subsidence in our study area, and the onset of the general uplift and tilting of the former basin area in the ECF with appearance of highlands and deep incised valleys instead of former flat lowland. This tectonic evolution resembles that of the NW margin of the Focşani Basin, which subsided during the Pliocene, was uplifted during the late Pliocene, resumed its subsidence during the earliest Pleistocene, and experienced a final period of uplift in the late Early Pleistocene (Necea et al. 2005).

The local tectonic influence for the Porat Fm. is related to the Reni–Izmail Trough; an active structure with block-type subsidence. An increase in thickness of the late Miocene and Pliocene units in the Reni–Izmail Trough across subsequent faults reveals the syndepositional character of the normal faulting (Fig. 8). Despite the additional accommodation space in comparison with northern regions, fluvial incisions did occur, as manifested by scoured contacts and the presence of gravelly basal horizons.

The features of the Reni–Izmail Trough and the presence of local rootless displacements in the Porat Fm. provide evidence for tectonic activity of the eastern part of the SE Carpathian foreland, which penetrated deeply into the platform region during the Pliocene and probably the Calabrian. This means that the SE Carpathian foreland basin was still in its constructive phase at this time, in line with fission track evidence from the adjacent part of the orogen (Sanders et al. 1999).

Porat Stage: fluvial system evolution in connection with basin history

During the late Miocene, the general trend of development of the ECF was characterized by replacement of the offshore environment by a terrestrial one. The latter was intimately associated with the evolution of fluvial systems, which came into being in basin-margin settings along the periphery of the Eastern Paratethys. The latter part of the evolution of the ECF is known as the Balta Fluvial Stage (Matoshko et al. 2016). The Balta Stage was followed by a marked transgression in the Early Pontian and subsequent retreat of the Paratethys from the East Carpathian foreland.

The next Porat Fluvial Stage began in the early Cimmerian. We distinguish the Near-Danube, Early Porat and Late Porat substages; they correspond to the Near-Danube and Porat formations as well as Dolynske Mb. (Fig. 2).

Near-Danube Substage: incision and its subsequent filling

On an early map by Muratov (1964), the Dacian and Black Sea basins were connected by a hypothetical river through which freshwater of the Dacian Basin flowed into the brackish Black Sea during the Cimmerian. This river has subsequently been called the "Galaţi Passage" (Saulea et al. 1967), simply the "strait" (Mokriak et al. 2008), the "Reni Strait" and the "Reni Sill" (Popescu et al. 2009), the "Scythian Gateway" (Munteanu et al. 2012) or the Barlad Strait (Palcu et al. 2017). While considering this area very important for the connection–disconnection history of the Dacian and Black Sea basins, none of these authors actually cited data on its Pliocene–Quaternary geology. As we shall show below, offshore, terrestrial and river conditions succeeded each other in the passage area more than once during the Cimmerian and Kuialnykian times.

The strip of Cimmerian marine muds along the Galaţi Passage (Mokriak et al. 2008) indicates a relatively high sea-level stand and establishment of a connection between the Dacian and Black Sea basins at the beginning of the Cimmerian. Subsequently, a marked regional base-level fall (Matoshko et al. 2009) very likely led to overflow of the Dacian Basin into the Black Sea during the first half of the Cimmerian (Fig. 10a). This generated the observed incision in the area of the Reni–Izmail Trough, which was followed by deposition of the Near-Danube Suite in the incised canyon. The presence of the brackish molluscs in the lowest muds of this suite (Gozhik & Chirca 1973) may indicate re-establishment of a narrow, 10–20 km wide strait. The early Cimmerian corresponds to the Bosphorian (Late Pontian) of the Dacian Basin in the latest timescales (Krijgsman et al. 2010; Krijgsman & Piller 2012; Jorissen et al. 2018). Base-level variations within the Bosphorian of the Dacian Basin are poorly documented and it is not clear if the events we observe in the Porat area are clearly expressed there.

Early Porat Substage: genesis of a large alluvial basin infill

The onset of deposition of the Porat Fm. probably came in the Late Cimmerian (Dacian) (Fig. 2), when the sea level had relatively stabilized (Fig. 10b). The major Early Porat Substage of deposition lasted from the middle Zanclean (about 4.7 Ma) to the late Gelasian (about 1.8–1.9 Ma). During the Dacian Stage, the Dacian Basin was progressively infilled from the west to the east, as indicated by the gradual replacement of marine sedimentation by a fluvio–lacustrine environment (Jipa & Olariu 2009; Olariu et al. 2018). The Dacian Basin subsequently became a fresh-water and predominantly fluvial environment by the beginning of the Romanian (4.2 Ma; Jipa & Olariu 2009; van Baak et al. 2015). Interfingering of the Porat Fm. sands with frequent muds with fresh- and possibly brackish water fauna (Gozhik & Chirca 1973) shows that brackish-lacustrine conditions alternated with fluvial ones in the Galati Passage. Van Baak et al. (2015), found that typical lymnocardiide bivalve genera occur in a thin interval of the Slanicul de Buzau section on the western margin of the Focsani Depression, dated magnetostratigraphically at 2.95–3.20 Ma. This was interpreted to reflect a short-lived incursion of the Black Sea during a base-level high stand (Plescoi flooding event). This might possibly have a relation with the time the Galati Passage developed as a lake.

While synsedimentary normal faulting would have helped to keep the Galati Passage open, at some point the Porat infill may have restricted it (Fig. 10c). This can have contributed to the freshening of the Dacian Basin during the Romanian. It is likely that part of the Porat infill was also directed towards the Kuialnykian Black Sea Basin.

Late Porat Substage: appearance of Dolynske Valley and arrival of the paleo-Danube to the Black Sea

The cutting of the Dolynske Valley and its subsequent infill was a sharp event signifying the complete infilling of the Dacian Lake and spillage of the Danube and its tributaries into the Black Sea Basin. The specific mineral composition of the Dolynske Mb. sand is very similar to that of sand from the present-day Danube and its tributaries in the Western Dacian Basin (de Leeuw et al. 2018). This means that the Dolynske Mb. provides the first tangible evidence for the presence of the Danube in the Galati Passage, as earlier supposed by Konstantinova (1967). We infer that the Danube and its main tributaries the Siret and the Prut paved their final way through the area of the former Dacian Lake and through the Galaţi Passage at approximately 1.9–1.8 Ma BP (Fig. 10d), based on the age of the youngest mammal fossils found in the Dolynske Mb. This age is much younger than the 4 Ma age inferred by Olariu et al. (2018), but in agreement with reconstructions by Andreescu (2009) and Black Sea sediment provenance data (de Leeuw et al. 2018). As was stated above, subsequent river entrenchment during the Calabrian into deposits of the Dolynske Mb. meant the end of the Porat Stage. It led to transformation of the previous coastal lowland into the elevated and erosionally dissected plain with incised river valleys that it is today.

View on landscape–climatic features from sedimentary data

As indicated, there is a rich record with information on the regional climate during deposition of the Porat Fm. However, this record is very contradictory, which, as we will show, is related to the nature of the sedimentary environment.

It is noteworthy that the lower part of the Porat Fm. includes remains of large mammals belonging to many different biotopes (Ali-Zade et al. 1972): the riverside (beavers, water pigs, elephants *Deinotherium*, large cats, hippopotamus); the forest (bears, tapirs, macaques, monkeys *Dolichopithecus*, mastodons *Borsoni*, squirrels, deer *Cervus unicolor*, roe, lynxes); the forest-steppe (mastodons of Anancus family, rhinoceros, hipparions, bush-antlered deer, hares) and the arid steppe (camels, antelopes, hyenas, corsac foxes, pikas).

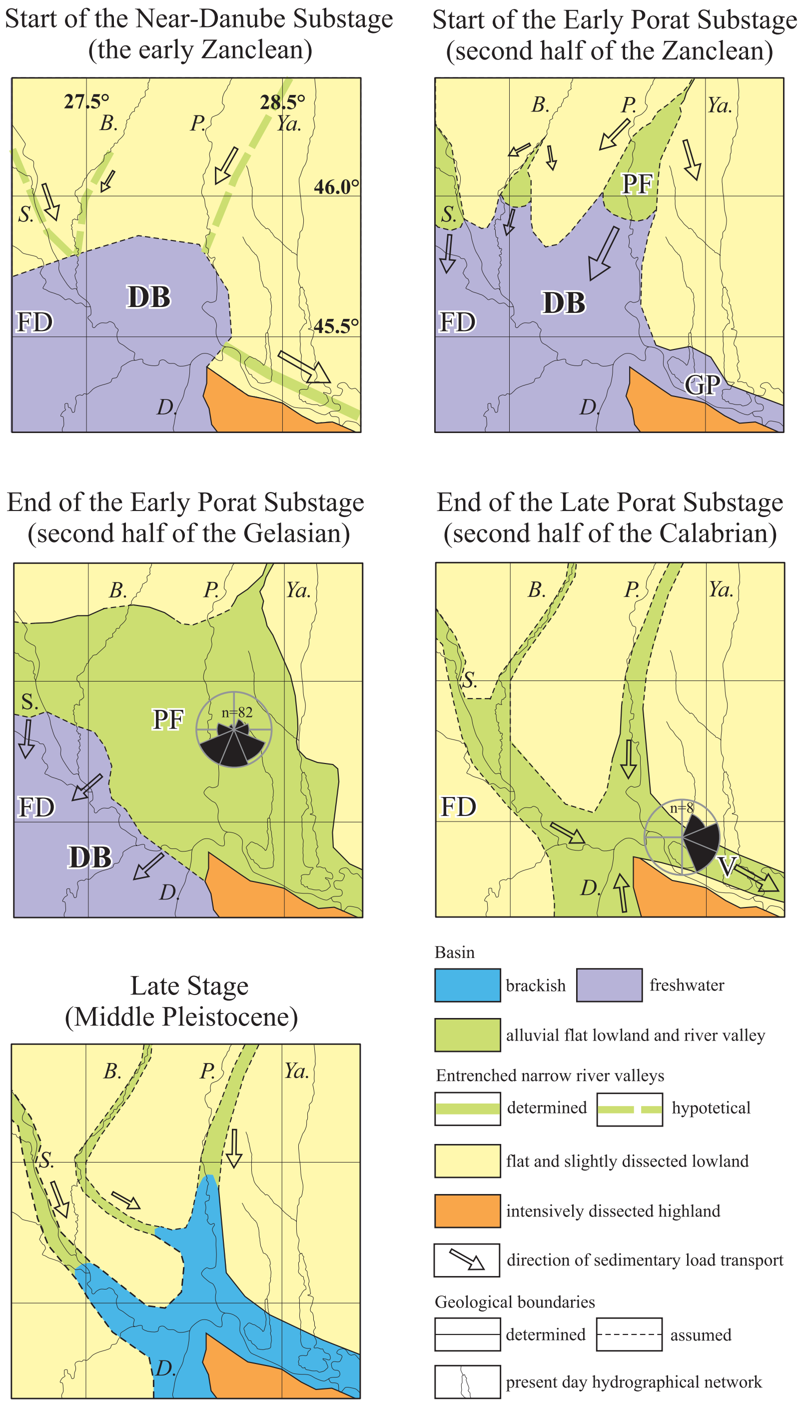

Fig. 10. Fluvial sedimentary system evolution during the Porat Stage in comparison with the Late Stage. Some maps of the Porat Stage are accompanied by rose diagrams of the paleocurrent direction based on cross-bedding dip determinations. DB — Dacian Basin, PF — Porat Fan, V — Porat–Prut, Siret and Danube valleys, FD — Focşani Depression (basin depocenter); rivers: S. — Siret, B. — Bârlad, P. — Prut, Ya. — Yalpukh, D. — Danube. Details see in the text.

The early diagenetic features of the Porat Fm. (reddish weathering crust and soils with carbonate nodules) that were noted before (e.g., Rengarten & Konstantinova 1965; Sinegub 1969; Hubca 1982) and observed during the course of this study confirm that the region had a semi-arid climate (e.g., Alonso-Zarza 2003).

Today, the Porat domain is a dry steppe dissected by narrow strips with river floodplains. Therefore, the stable combination of forests and steppes in the Pliocene–Lower Pleistocene requires an explanation, which we think is evident in the sedimentary data. The dynamic Porat infill provided surface water and maintained a relatively high groundwater level for the growth of woody vegetation and other riverside- and forest species in and close to the braided river belt. Ample precipitation of moisture in the Carpathian Mountains provided much runoff for the Porat and Siret rivers, which probably had a very regular and distinct high-mean water regime.

The Porat domain was thus a vast azonal landscape on a river plain surrounded by a dry steppe zone with a generally semi-arid climate. The warm and humid conditions of the Cimmerian may have shifted the landscape zones southwards. Faunal elements characteristic of different zones nevertheless continued to coexist in Gelasian–Calabrian times, which are frequently considered by most researchers to have been a colder and drier period in this area. The above interpretation from the point of view of the fluvial process does not pretend to explain all the contradictory questions in the evolution of the biota, but speaks of the need for its inclusion in further paleogeographic studies.

Conclusion

The focus of our attention was the Pliocene to Calabrian Porat Fm., which occurs on the borders of Romania, Moldova and Ukraine, along the NE margin of the Dacian Basin. The Porat Fm. is interpreted as a large, north–south directed, wandering sandy alluvial basin infill with a generally very uniform aggradational structure, consisting of cyclic channel–floodplain units deposited by relatively powerful braided rivers. The sediment supply for the Porat infill came from reworking of the late Miocene Balta Fm. and the overlying Pontian shallow marine strata in addition to the significant contribution from the Carpathians. The Porat basin infill generally overlies shallow marine strata deposited during the Early Pontian transgression with a disconformity, while it rests on early Cimmerian strata along its southern margin. In this southern strip, a Dolynske Mb. is distinguished, with a different alluvial facies and sediment composition from the rest of the Porat Fm., and representing the infill of a large west-east running paleo-valley. We infer the Dolynske Mb. to have been deposited by the Danube based on a similarity in heavy mineral assemblages. The Danube, with its continental-scale drainage basin stretching across the Alps, Dinarides and Carpathians, has thus been supplying sediment to the Black Sea since at least 1.9–1.8 Ma BP.

Aggradation of the Porat basin infill was in the first place governed by down-warping of the Dacian Basin as the main and stable tectonic background. The end of the Porat Stage (the end of the Calabrian) is associated with final inversion of crustal movements, leading to uplift and tilting of the whole Porat area and whole basin of the Porat River. This inversion corresponded to completion of the construction orogenic phase in Easternmost Carpathians and the final establishment of terrestrial conditions in the Dacian Basin, what resulted in the onset of the last phase of the fluvial development continuing from the end of the Calabrian till today. The south-eastern part of the Porat area was especially dynamic in the tectonic respect. It was manifested in pronounced local block subsidence along the New Trotus and St. George faults. This led to formation of the Reni–Izmail Trough, which is paleogeographically known as the Galaţi Passage. This trough formed the connecting gateway between the Black Sea and Dacian Basin during the Pliocene–Gelasian–Calabrian. It allowed for overflow of the Dacian Basin into the Black Sea during Black Sea base-level lowstands and for brackish-marine ingressions into the Dacian Basin during Black Sea base-level highstands. The trough also manifests some of the most impressive river entrenchments and the arrival of the Danube to the Porat area around 1.9–1.8 Ma BP.

A stable delivery of water from the Carpathians allowed for the existence of the Porat infill in a semi-arid climatic zone. As a result the Porat area displayed an azonal forest–steppe landscape with various faunal biotopes within coastal alluvial lowland.

The relatively thin Porat Fm. is key for understanding not only the development of its analogues within the north-western coastal regions of Black Sea (such as Kuialnykian, Dniester Liman and Roksolany formations), but also for correlation of various events and phenomena in the Pliocene–Quaternary of the residual Eastern Paratethys basins. Together with the Balta Fm. it contains valuable information for further in-depth study of the Carpathian foreland and its tectonic–sedimentary–relief evolution.

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Appendix

Location of cited sites.

Site name	East longitude	North latitude	Number in Fig. 1
Albota de Jos	28.4707	45.9441	31
Andrușul de Sus	28.2575	46.0076	27
Bălăbănești 1	27.7305	46.0915	5
Bălăbănești 2	27.7331	46.0908	6
Berești	27.8904	46.1100	4
Bolgrad 1	28.6560	45.6758	49
Bolgrad 3	28.6500	45.6570	52
Borceag	28.4871	46.0651	23
Budăi 1	28.4634	45.8353	36
Budăi 2	28.5035	45.8110	38
Cahul 2	28.2357	45.8811	34
Chioselia	28.4124	46.1403	17
Chioselia Mare	28.4636	46.1030	20
Ciobalaccia 1	28.2986	46.1679	15
Ciobalaccia 2	28.2752	46.1520	16
Cislita–Prut	28.1723	45.5350	60
Cişmichioi 1,2	28.3892	45.5435	59
Cîşla	28.3337	46.1352	18
Cociulia 1	28.3972	46.3632	12
Colibași-Brînza	28.1741	45.6907	48
Colibași 1	28.1849	45.6970	44
Colibași 2	28.2088	45.7334	46
Crăciun	28.3593	46.2290	14
Dermengi	28.4125	45.8736	35
Dolynske 1	28.3088	45.4848	65
Dolynske 2	28.3143	45.4722	66
Dolynske 3	28.3151	45.4541	68
Dolynske 4	28.3265	45.4526	69
Etulia Noua 6	28.4472	45.5405	61
Etulia Noua 2	28.4352	45.5198	62
Flocoasa	28.2721	46.1369	19
Foltești	28.0583	45.7241	8
Frumusica	28.4691	46.0807	21
Gavanoasa	28.7744	45.3961	43
Giurgiulești 1	28.1994	45.4944	64
Giurgiulești 2	28.1829	45.4837	67

Site name	East longitude	North latitude	Number in Fig. 1
Hîrtop-Balabanu	28.5181	45.9310	32
Huluboaia-Doina	28.3178	46.0819	22
Kotlovyna	28.5868	46.5188	63
Lărguța	28.3019	46.2823	13
Ljdileni 1	28.0328	45.6559	9
Ljdileni 2	28.0468	45.6380	9
Lucești	28.3186	45.9911	28
Lymanske 1	28.4124	45.4196	70
Malusteni 1	27.9178	46.1908	1
Manta	28.2155	45.7963	41
Manzatesti	27.8767	46.1658	3
Moscovei	28.3012	45.9227	33
Musaitu	28.5035	45.8110	40
Pelinei	28.3256	45.8179	39
Slobozia Oancea	28.1061	45.8876	7
Spicoasa	28.3785	46.0445	24
Tartaul de Salcie	28.4213	45.9717	29
Tătărești 1	28.3511	46.0122	25
Tătărești 2	28.3537	46.0390	26
Topolyne	28.6511	45.6111	55
Trifestii Noi	28.3563	45.9577	30
Tulucești	28.0418	45.5610	10
Tutcani	27.9474	46.1730	2
Ursoaia	28.3223	45.8567	37
Valeni - Slobozia Mare 1	28.1666	45.6075	57
Valeni - Slobozia Mare 2	28.1696	45.6118	56
Valeni - Slobozia Mare 3	28.1921	45.5987	58
Valeni 1	28.1731	45.6590	53
Valeni 2	28.1766	45.6217	54
Vanatori	28.0361	45.5302	11
Vynogradivka1	28.5667	45.7107	45
Vladimirovca	28.3567	45.7887	42
Vulcănești 1	28.4463	45.6846	47
Vulcănești 2	28.3680	45.6756	50
Vulcănești 3	28.3664	45.6806	51

Supplement

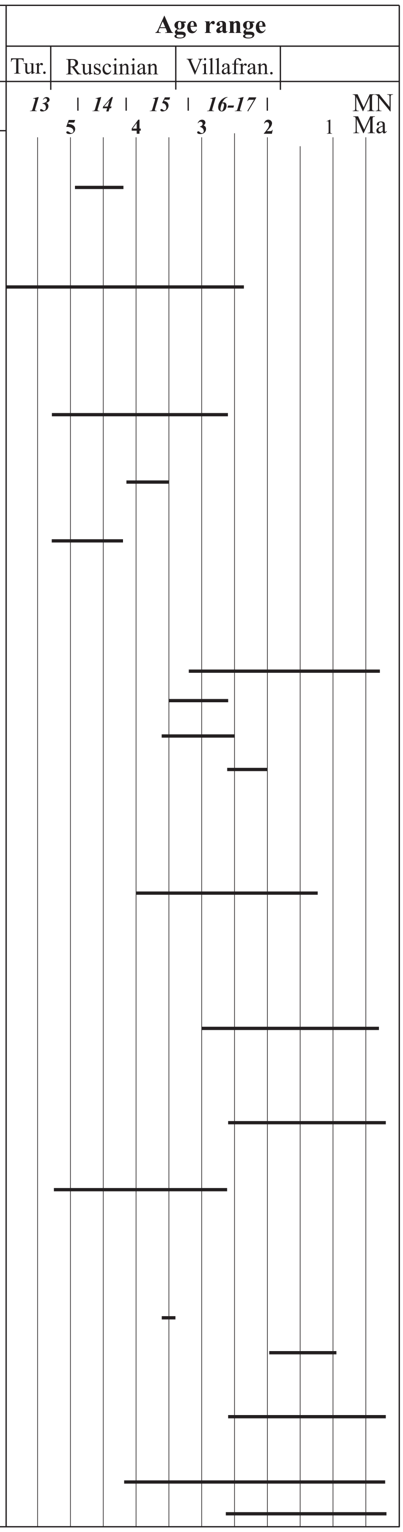
Table S1: Age of Porat Fm. by index-representatives of terrestrial large mammals which appearance, living frame or extinction falls in the Pliocene–Early-Middle Pleistocene. The determination of taxa or reference in summaries are made for: Konstantinova 1967 (Alexeeva L.I., Gromova I.M., Kalke G.D.); Radulescu et al. 2003 (Athanasiu; Simonescu, Samson, Radulescu; Samson); Ali-Zade et. al. 1972 (Alexeeva L.I., Garutt V.E., Dubrovo I.A.); Hubca 1982 (Khomenko, Krokos; Alexeeva L.I.). Living frame is according to: (1) Radulescu et al. 2003; (2) Vislobokova & Tesakov 2013; (3) Paleobiology Database 2018; (4) Vangengeim et al. 1995; (5) Forsten 1996. Abbreviations: Tur. — Turolian, Villafran. — Villafrancian, MN — mammal units of Western Europe (Augustí et al. 2001). For estimation of rejuvenation of mammal ages southwards see the locations of sites in Fig. 1 in the text.

Site	Source	Family, genus, species	Age range Tur. | Ruscinian | Villafran. MN: 13 | 14 | 15 | 16-17 Ma: 5, 4, 3, 2, 1
Large mammals			
		*Elephantidae**	
Tuluceşti	Radulescu et al. 2003	*Archidiskodon (Mammuthus) rumanus* Ştefănescu 1924 (1)	
Kotlovyna	Konstantinova 1967	*Archidiskodon gromovi* Garutt et Alexeeva 1965 (2)	
Kotlovyna, Dolynske, Cişmichioi	Konstantinova 1967 Ali-Zade 1972	*Mammuthus meridionalis* Nesti 1825 (1, 2, 3)	
		Gomphotheriidae	
Etulia Nouă Dermengi, Găvănoasa, Vladimirovka, Tătăreşti, Luceşti, Pelinei, Malusteni, Tulucheşti	Konstantinova 1967 Hubca 1982 Radulescu et al. 2003	*Anancus arvernensis* Cr. et Job. 1828 (3)	
		Mammutidae	
Tulucheşti Dolynske Malusteni	Radulescu et al. 2003 Sincov 1897 Radulescu et al. 2003	*Mastodon borsoni* Hays 1834 (2)	
		Camelidae	
Musaitu, Găvănoasa, Etulia	Vangengeim et al. 1995	*Paracamelus* Schlosser 1903 (3, 4)	
Bereşti Dermengi, Măluşteni	Radulescu & Samson 2001 Hubca 1982, Radulescu et al. 2003	*Paracamelus alexejevi* Khavesson 1950 (3)	
		Equidae	
Pelinei	Hubca 1982	*Hipparion crassum* Gervais 1859 (3)	
Măluşteni	Radulescu & Samson 1996	*Allohippus* (1, 3)	
Cişmichioi, Dolynske	Konstantinova 1967; Ali-Zade 1972	*Equus Stenonis Cocchi* (5)	
		Bovidae	
Cişmichioi, Giurgiuleşti, Dolynske	Konstantinova 1967; Ali-Zade 1972	*Bison suchovi* (3)	
		Cercopithecidae	
Budăi, Măluşteni, Bereşti	Hubca 1982 Radulescu et al. 2003	*Dolichopithecus* ruscinensis Deperet 1889 (1, 4)	
		Rhinocerotidae	
Pelinei	Hubca 1982	*Dihoplus megarhinus* de Christol 1835 (3)	
Dolynske, Giurgiuleşti	Konstantinova 1967; Ali-Zade 1972	*Stephanorhinus (Dicerorhinus) etruscus* Falconer 1868 (3)	

*According to (Lister & van Essen 2003) all the noted elephants are referred to genus *Mammuthus* Brookes, 1828 (including two species: *M. rumanus* and *M. meridionalis*) evolved from the end of Ruscian up to the Middle Pleistocene.

Table S2: Age of Porat Fm. by index-representatives of terrestrial small mammals which appearance, living frame or extinction falls in the Pliocene-Quaternary. The determination of taxa in summaries are made for: Konstantinova 1967 (Alexeeva L.I., Odintsova I.A., Gromov I.M., Alexandrova L.P., Shevchenko A.I.); Hubca 1982 (Alexeeva L.I.); Ali-Zade et al. 1972 (Gromov I.M., Topachevskii V.A., Shushpanov K.I., Alexandrova L.P.). Living frame is according to: (1) Paleobiology Database 2018; (2) Vangengeim et al. 1995; (3) Vangengeim & Tesakov 2008; (4) Čermák 2010; (5) Fejfar et al. 2011; (6) Radulescu & Samson 1996; (7) Tesakov 2004; (8) Maul & Markova 2007; (9) Gromov & Polyakov 1977; (10) Bell & Bever 2006; (11) Vislobokova & Tesakov 2013; (12) Rümke 1985. Abbreviations: see in Table S1. For estimation of rejuvenation of mammal ages southwards see the locations of sites in Fig. 1 and description in the text.

Site	Source	Family, genus, species
Small mammals		
		Leporidae,
Budăi Bereşti	Vangengeim et al. 1995 Radulescu & Samson, 2001	*Trischizolagus dumitrescuae* Radulescu and Samson 1967 (1)
		Ochotonidae
Cişmichioi	Shushpanov 1977	*Proochotona (Ochotona) eximia* Khom. 1914 (1)
Etulia Noua, Tătăreşti	Hubca 1982	
Musaitu	Shushpanov 1980	
Bereşti Pelinei	Radulescu & Samson 2001 Erbajeva & Shushpanov 1988	*Pliolagomys gigas* (3, 4)
Măluşteni	Čermák 2010	*Ochotona ursui* (4)
		Cricetidae (Arvicolinae)
Etulia Noua, Musaitu	Hubca 1982	*Promimomys* (5)
Budăi, Musaitu, Kotlovina	Vangengeim et al. 1995	
Măluşteni	Radulescu & Samson 1996	*Mimomys* moldavicus (6, 1)
Giurgiuleşti*	Tesakov 2003	*Mimomys hajnackensis* (7)
Giurgiuleşti*	Tesakov 2003	*Mimomys hintoni* Fejfar (7)
Etulia Noua, Dolynske,	Konstantinova 1967	*Mimomys reidi* Hinton (5, 8)
Valeni, Cişmichioi	Shushpanov 1980 Ali-Zade et al. 1972	
Etulia Noua	Konstantinova 1967	*Dolomys* Nehring 1898 (1, 9)
Dolynske, Valeni, Giurgiuleşti*	Ali-Zade et al. 1972 Shushpanov 1980 Tesakov 2003	*Dolomys milleri* Nehring 1898
Kotlovina, Etulia Noua	Konstantinova 1967	*Allophaiomys pliocaenicus* Kormos 1932 (10)
Cişmichioi	Shushpanov 1977	
Kotlovina, Cişmichioi	Konstantinova 1967	*Pliomys* Méheli 1914 (1,5)
Etulia Noua, Giurgiuleşti,* Cişmichioi, Kotlovina	Konstantinova 1967	*Pliomys hungaricus* Kormos 1934 (1,5)
Dolynske	Ali-Zade et al. 1972	
Giurgiuleşti*	Tesakov 2003	*Pitymimomys inceptor* sp. nov. (7)
Cişmichioi	Ali-Zade et al. 1972	*Lagurus (Laurodon) arankae* (11)
		Cricetidae (Cricetinae)
Cişmichioi	Shushpanov 1977	*Cricetus cricetus* (1)
		Talpidae
Musaitu	Hubca 1982	*Talpa minor* Freudenberg 1914 (1)
Cişmichioi	Shushpanov 1977	*Desmana thermalis* Kormos 1930 (12)



*Giurgiuleşti site of the Porat F. in some publications is called "Ripa Scorcelskaia" (name of the gully)