# **Reference Section of the Campanian Stage of the Southwestern Crimea: Problems of Substage Subdivision and Global Correlation**

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Abstract—Stratigraphy of Campanian deposits in the stratotype of the Kudrinskaya Formation in the Southwestern Crimea is revised. For the first time, integrated sedimentological, biostratigraphic (ichnofossils, cephalopods, inoceramids, foraminifers, dinocysts, nannoplankton, gilianelles), isotope-geochemical, paleo- and petromagnetic characteristics of the section were obtained. The boundary of the lower and upper Campanian is substantiated and confirmed by U–Pb dating of zircons from the well-known bentonite (kil) clay bed in the interval of 77–80 Ma. It is proposed to accept the Campanian Substage boundary of the General Stratigraphic Chart (for bipartite stage subdivision) at the top of the Chron C33r, located near the  $\delta^{13}$ C isotopic excursion "MCaE" – Mid-Campanian Event, near the first occurrence of the benthic foraminifer *Brotzenella monterelensis* and a number of other traditional biomarkers.

**Keywords:** Kudrino, Upper Cretaceous, stratigraphy, belemnites, ammonites, inoceramids, foraminifers, nannoplankton, dynocysts, gilianelles, magnetostratigraphy, Chron 33r, stable isotopes

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# **INTRODUCTION**

The Campanian-Maastrichtian deposits of the Southwestern Crimea are well known in publications due to their stratigraphic completeness and similarity with sections of Western Europe. Although this area has been studied by many generations of geologists, the sections require re-examination because of the definition of the stage boundaries and the substantiation of the substage boundaries. Previously, a number of sections spanning the boundary interval of the Santonian and Campanian stages and the lower part of the Campanian Stage in the area of the Aksu-Dere Ravine and the northern vicinity of the village of Kudrino were comprehensively studied (sedimentology, ichnofossils, macro- and microfauna, palynology, nannoplankton, isotopy, paleo- and petromagnetic methods) (Guzhikov et al., 2020, 2021a, 2021b) (Figs. 1, 3). In the level of their characterization, they are not inferior to the candidate for the not yet ratified global stratotype (GSSP) of the Campanian and are considered as an auxiliary section (Gale et al., 2023, p. 26).

In 2021, following Hancock and Gale (1996), we proposed to draw the Santonian-Campanian boundary according to the change in magnetic polarity at the base of chron C33r (Guzhikov et al., 2021b). At the same level, this boundary was shown in the previous studies (Gradstein et al., 2012, 2020; etc.), and currently this feature is accepted as the primary marker for defining the GSSP in the Bottaccione section (Gubbio, Italy; Gale et al., 2023). In this paper, we accept the afore-mentioned (but not yet approved) boundary between the Santonian and Campanian stages at the base of chron C33r of the Kudrino-2 section (Fig. 2).

The subdivision of the Campanian Stage into two or three substages is under discussion (Hancock and Gale, 1996; Gradstein et al., 2012, 2020; Baraboshkin et al., 2013), and there are no generally accepted criteria or proposals in this regard. Therefore, we took as a basis the bipartite subdivision of the Campanian in accordance with the current General Stratigraphic Scale of Russia (Olfer'ev and Alekseev, 2002).

In Crimea, the higher parts of the Campanian section and the Campanian-Maastrichtian boundary interval were comprehensively studied in the Beshkosh section (Baraboshkin et al., 2020), Chakhmakhly section and other sections (Guzhikova, 2019). The boundary interval of the lower and upper Campanian is the least characterized because it is generally very



**Fig. 1.** Location of the Kudrino-1, Kudrino-2, Kudrino-3 and Aksu-Dere sections (according to Guzhikov et al., 2020, 2021a, 2021b). In Fig. 1 lines of different thicknesses show various roads from highways (thick lines) to dirt roads (thin lines).

poorly exposed. Therefore, the purpose of this work was a comprehensive study of the stratotype of the Campanian Kudrino Formation (Plotnikova et al., 1984) near the village of Kudrino (section Kudrino-1, Figs. 1, 2a) to substantiate boundaries of the substages.

# MATERIAL AND METHODS

Field study and sampling of the section was conducted several times. The material we collected in 2002 (locality 2414) remained generally unpublished, except for data on foraminifers, mainly planktonic (data from L.F. Kopaevich (MSU) in Kopaevich and Khotylev, 2014; Kopaevich and Vishnevskaya, 2016). E.Yu. Baraboshkin, A.Yu. Guzhikov, A.G. Manikin, and V.A. Grishchenko repeated sampling in 2018 by (locality 3169). Oriented samples for various types of analysis were taken from 102 stratigraphic levels using the "sample-to-sample" system, with a section thickness of 94 m. Additionally, a small rock outcrop was studied in an abandoned quarry near the main section (Fig. 2b), where, in addition to finds of macrofauna



**Fig. 2.** Photographs of the studied sections. (a) General view of the section, approximate sampling track and position of the abandoned quarry (arrow); (b) photo of an abandoned quarry showing bentonite clay (Member XVII, below and to the left of the arrow), and the place where the ammonite was found (arrow).

and ichnofossils, a sample of bentonite clays was selected for subsequent isolation and dating of zircons by the U-Pb method (SHRIMP-II).

Description of the section, sedimentological, petrographic, ichnological studies, as well as a study of macrofaunal remains were conducted by E.Yu. Baraboshkin (MSU), magnetostratigraphic data were obtained by A.Yu. Guzhikov, V.A. Grishchenko (SSU), isotope dating analysis was carried out by V.V. Akinin (SVKNII FEB RAS), palynological analysis was carried out by G.N. Alexandrova (GIN RAS), benthic foraminifers were studied by I.P. Ryabov (SSU), nannoplankton—M.A. Ustinova (GIN RAS), gilianelles— V.S. Vishnevskaya (GIN RAS), and data on the geochemistry of stable isotopes were obtained by N.A. Rtishchev (MSU, GIN RAS) under the leadership of B.G. Pokrovsky (GIN RAS) in the Laboratory of Isotope Geochemistry and Geochronology of the GIN RAS.

Samples of macrofauna and ichnofossils are housed in the Earth Science Museum of Moscow State University (collections 149 and 140, respectively), microfossil preparations are housed in the laboratories of the Geological Institute of the Russian Academy of Sciences, and benthic foraminifers are housed in the collection of I.P. Ryabov.

#### SECTION DESCRIPTION

The Kudrino-1 section is located in the Bakhchisarai region of the Republic of Crimea, southwest of the city of Bakhchisarai, on the right bank of the Kacha River (Figs. 1a–1c). The beds lie conformably and are dipping northwest. The dip azimuths vary from 250° to 290°, and dip angles range from 7° to 10°. The section of the Kudrino Formation was studied along one of the gullies cutting through the slope of the watershed on the southwestern vicinity of the village of Kudrino; its beginning has coordinates  $44^{\circ}42'16.5''$  N,  $33^{\circ}56'25.9''$  E; coordinates of the abandoned quarry:  $44^{\circ}42'20.4''$  N,  $33^{\circ}56'29.4''$  E.

The lower part of the section (members XVI-XVIII of the Upper Cretaceous sequence according to Alekseev (1989)) was studied in the Kudrino-2 section (Fig. 3), data for which were published previously (Guzhikov et al., 2021a) and are not repeated here. The correlation with the Aksu-Dere section was drawn at the base of the Bolivinoides pustulata Zone and the top of the Pseudogavelinella clementiana clementiana Zone using benthic foraminifers (BF), while the correlation with the Kudrino-1 section was proposed indirectly through the Aksu-Dere section (Fig. 3). It is not possible to log the sections using other methods considering lithological characteristics and in the state of existing exposure. Between the Kudrino-1 and Kudrino-2 sections there is a gap in exposure, the thickness of which is estimated at 57 m (see section "Magnetostratigraphy"). According to the correlation, the indexation of the upper member of the Aksu-Dere and Kudrino-2 sections has been changed compared to that in Guzhikov et al. (2021a, 2021b). Outcrops in the abandoned quarry duplicate the main section of Kudrino-1 and are easily compared with it based on the thickest bed of bentonite (kil) clays; therefore, a description of this outcrop is not given separately. The studied section is represented by the following sequence (from bottom to top, Fig. 3):

**Submember XVId1** (overlies Submember XVId: see Guzhikov et al., 2021a). Light gray and greenish clayey marls (0.1–0.6 m), alternating with more strongly clayey marls and calcareous clays (0.1–0.15 m). The thickness of all beds increases slightly up the section. In thin sections, the rocks are represented by foraminiferal wackestones. The submember contains rare remains of sponges and ichnofossils *Planolites* isp., *Chondrites* ispp., *Zoophycos* isp., rare *Thalassinoides* isp. Visible thickness 6.4 m.

No. 2

2024



**Fig. 3.** Correlation of lower Campanian deposits in the area of the village of Kudrino and the Aksu-Dere Ravine (according to Guzhikov et al., 2020, 2021a, 2021b). The section names have locality numbers in parentheses.

**Submember XVId2.** Alternation of bioturbated marls (0.3-0.6 m) and clayey marls (0.15-0.25 m) with rare interbeds of calcareous clays. The Submember begins with a thick (~1 m) bed of foraminiferal wackestones (Pl. I, fig. a), containing in the middle part elongated nodules of light gray chert (up to  $0.15 \times 0.25 \text{ m}$ ). At the top there is a thick (0.7 m) interbed of clayey limestones, forming a small ledge, below which there are several hardground surfaces (HG) and a horizon of weathered pyrite concretions. The member contains burrows of *Thalassinoides* isp. and *Chondrites* isp. The thickness is 6.9 m, and the total thickness of Member XVI, including the gap, is presumably about 77–80 m.

**Member XVII.** Alternation of clays, greenish bentonite clays and light gray marls, microscopically represented by foraminiferal-calcisphere packstones and mudstones (Pl. I, fig. b). Member begins with a thin (0.1 m) bed of bentonite clay with small limonitized pyrite concretions and ends with a thick (0.3–0.4 m) bed of bentonite clay, which was mined in a now abandoned quarry. The top of this bed shows signs of erosion. In the upper part of the submember, several HG surfaces are present, and the marls contain remains of sponges and bioturbations of *Chondrites* isp. Thickness 6.7 m.

Member XVIII. This member is subdivided into two submembers.

Submember XVIIIa. Clayev limestones and marls with thin (0.02-0.05 m) interbeds of gray clays or highly clayey marls. At the base there are two thick ( $\sim 1 \text{ m}$ ) foraminiferal wackestones with single grains of glauconite (Pl. I, fig. d), the lower of which contains *Pachydiscus* (Pachvdiscus) launavi (De Grossouvre) was found (Pl. II, fig. 3; Baraboshkin, 2023). Up the section, the thickness of the limestones decreases; they are represented by calcisphere-foraminiferal wackestones (Pl. I, fig. c). In the spoil heaps from the rocks of this submember, a rich assemblage of ichnofossils was collected: Zoophycos villae Massalongo, Chondrites caespitosus (Fisch.-Oost.), Palaeophycus tubularis Hall, P. heberti (de Saporta) (Baraboshkin, 2020; Guzhikov et al., 2021a), Planolites isp., Chondrites isp. Sphaeroceramus cf. sarumensis (Pl. 2, fig. 4), and Cataceramus sp. ex gr. C. dariensis (Dobrov et Pavlova) (Woods) was also found here (Pl. II, fig. 5). Thickness 9 m.

**Submember XVIIIb.** Finely rhythmic alternation (0.15-0.2 m) of bioturbated marls and loose clayey marls (0.05 m) with *Chondrites* burrows. The thickness of the submember is 6 m, and the thickness of the entire Member XVIII is 15 m.

**Member XIX.** The member contains several submembers, of which only the lower one is present in the studied section.

Submember XIXa. Thickly rhythmic alternation (0.25-0.3 m) of bioturbated and loose clay marls of

approximately equal thickness with Chondrites burrows. Microscopically, these are foraminiferal mudwackestones, sometimes with inclusions of foraminiferal packstones (with broken tests of benthic and planktonic foraminifers), which are probably coprolites, with fragments of the prismatic layer of inoceramid shells, crinoidal fragments and single silty quartz grains (Pl. I, fig. f). Replacement of foraminiferal tests with silica is frequently observed. Section 3169/82 is a silty bioclastic packstone with fragments of foraminifers, bivalves, small (0.05–0.07 mm) spherical formations composed of fine-crystalline carbonate (possibly a product of the replacement of calcispheres, chambers of foraminifers and radiolarians), undetectable bioclasts, phosphatized foraminifers, glauconite grains and relatively numerous silty quartz grains (Pl. I, fig. e). This thin section indicates the presence of a small gap, which is not visually detectable in the section. The submember contains remains of bivalve mollusks Spondylus sp. indet, and fragments of rostra of Belem*nitella* sp. indet. were found in the scree, near the top. Visible thickness 29 m. The upper part of this submember, about 11 m thick, is exposed 350 m to the west, on the adjacent watershed (section Kudrino-3), where it is overlain by irregularly platy clayey limestones of Submember XIXb, in the lower six meters of which rostra of Belemnitella mucronata (v. Schlotheim) are found in the scree) (Pl. II, figs. 1, 2). Thus, the total thickness of Submember XIXa in the Kudrino area is about 40 m.

#### **DEPOSITIONAL SETTINGS**

## Petrography

The microscopic structure of the rocks and the change in the ichnofossil assemblage (Baraboshkin, 2020; Guzhikov et al., 2021a) confirm the general trend of deepening of the basin in the first half of the Campanian (Alekseev, 1989; Alekseev and Kopaevich, 1997; etc.). As was shown in the study of the Aksu-Dere and Kudrino-2 sections (Guzhikov et al., 2021a), the composition of the basement rocks of the Campanian corresponds to the standard microfacies 3 "pelagic mud-, wacke-, packstone with planktonic microfossils", characterizing basinal facies or deep shelf (Flügel, 2010). At the same time, there is a clear trend from foraminiferal packstones of the Campanian base to wacke- mudstones of the higher part of the section. At the same time, relatively rich foraminiferal assemblages are replaced upward by impoverished assemblages with rare Globigerina-like forms; the tests decrease in size, and some of them are replaced by silica. This trend is generally reflected in the Kudrino-1 section, where foraminiferal wackestones predominate. In the lower part of the section, a significant number of calcispheres were recorded in places (Submember XVII; Pl. I, fig. b), indicating stress conditions in the basin. Individual levels associated with small gaps show single grains of glauconite (base of Submember XVIIIa; Pl. I, fig. d). Fine silty quartz grains, presumably of aeolian origin, are extremely rare (Submember XIXa; Pl. I, fig. f). These features clearly indicate the deepening of the basin and the development of deep shelf settings with clavey-carbonate deposition. In the interval of samples 3169/85-3169/90, signs of some shallowing are recorded: increase in saturation of the rock with large bioclasts, including tests of benthic foraminifers and fragments of echinoderms. A specific feature of the studied interval of the Kudrinskava Formation is the presence of bentonite clays (Submember XVII), deposited in the environment of subaqueous weathering of layers of volcanic ash of andesitic composition (Lebedinsky et al., 1974). Their formation was associated by V.I. Lebedinsky with volcanism that took place in the Crimean Plain, however, later the Late Albian age of the volcanoes of the Karkinit Trough was established, and currently the appearance of bentonite clays is explained by the supply of volcanic material from the Pontides located to the south (Nikishin et al., 2013). If the latter is true, then the sources of airborne ash were located at a distance of at least 400–600 km south of the study area.

#### Ichnology

Ichnofossils have been briefly described and illustrated previously (Baraboshkin, 2020; Guzhikov et al., 2021a). In an abandoned quarry (Member XVII–Submember XVIIIa), *Zoophycos villae* Massalongo, *Chondrites caespitosus* (Fisch.-Oost.), *Chondrites caespitosus* (Fisch.-Oost.), *Palaeophycus tubularis* Hall, *P. heberti* (de Saporta), and mostly *Thalassinoides suevicus* (Reith), *Chondrites* isp., and *Planolites* isp. This ichnoassemblage characterizes the *Zoophycos* ichnofacies (Baraboshkin, 2020; Guzhikov et al., 2021a), replacing the relatively shallow Upper Santonian *Cruziana* ichnofacies, which, together with a change in the petrographic composition of the rocks, indicates a transgressive trend and deepening of the basin.

## **Biostratigraphy**

# Macrofauna

Very few macrofaunal remains were found in the studied interval.

The Early Campanian ammonite *Pachydiscus* (*Pachydiscus*) launayi (De Grossouvre) was found in an abandoned quarry, 20 cm above the top bentonite clay bed, and the marls of the quarry overburden (3–4 m above the bentonite clay bed, Submember XVIIIa) contain inoceramids: Early Campanian *Sphaeroceramus* cf. sarumensis (Woods) and *Cataceramus* sp. ex gr. *C. dariensis* (Dobrov et Pavlova) (Pl. II, figs. 4, 5). These records clarify existing datings of the stratigraphic position of bentonite clays and Submember XVIIIa based on planktonic (Kopaevich and Vishnevskaya, 2016) and benthic (this paper) foraminifers.

*Pachydiscus (Pachydiscus) launayi* (Pl. II, fig. 3; (Baraboshkin, 2023)) is represented by the mold of a large phragmocone 170 mm in diameter, with the very beginning of the body chamber, strongly and somewhat asymmetrically compressed laterally. Despite the not entirely ideal state of preservation, the specific characteristics are quite distinct, and therefore the specimen is not identified in open nomenclature.

The species *P. (P.) launayi* characterizes the lower Campanian, as evidenced by its occurrences in sections in Western Europe, the Arabian Peninsula and Madagascar. Information about its presence in the Campanian of the Caucasus and the Russian Plate seems problematic due to the poor preservation of the material (Baraboshkin, 2023).

Occurrences of *P. (P.)* cf. *launayi* were previously recorded from Crimea, from the Kuibyshev District (Belbek River) from "indistinctly bedded marls" with *Belemnitella mucronata* and from the Bakhchisarai District (Mikhailov, 1951, p. 61), but without an illustration. Therefore, it is difficult to judge the degree of reliability of these identifications.

The inoceramid *Sphaeroceramus* cf. *sarumensis* (Pl. II, fig. 4) is represented by a deformed right valve with a preserved shell layer. *S. sarumensis* is the index species of the lower Campanian Sphaeroceramus sarumensis–Cataceramus dariensis Zone (and in the tripartite subdivision, the upper part of the lower–lower part of the middle Campanian) (Walaszczyk, 1997). It is found in Campanian sections of Western Europe, the Northern Caucasus, and North America (Walaszczyk et al., 2001).

*Cataceramus* sp. ex gr. *C. dariensis* (Pl. II, fig. 5) is represented by the mold of the right valve with fragments of the shell bed. The crown region is characterized by geniculate growth and clockwise rotation,

**Plate I.** Petrographic characteristics of the section. (a) Sample 3169/10, foraminiferal wackestone, Submember XVId2; (b) Sample 3169/20, foraminiferal-calcisphere pack-wackestone, Member XVII; (c) Sample 3169/30, calcisphere-foraminiferal wackestone, Member XVIIIa, marginal part of a *Planolites* isp burrow. (Pln); (d) Sample Kr18-4, foraminiferal wackestone, base of Submember XVIIIa, at the site of the ammonite find; (e) Sample 3169/82, silty bioclastic packstone with glauconite grains and phosphatized foraminifers, middle part of Submember XIXa; (e) Sample 3169/100, foraminiferal packstone—coprolite fragment (?) in foraminiferal packstone, upper part of Submember XIXa; (b) Sample 3169/100, foraminiferal packstone—coprolite fragment (?) in foraminifers, pf—planktonic foraminifers: G—globotruncanids, Gb—globigerinids, H—heterochelicids; cs—calcisphaeres, ph—phosphatized foraminifers; pl—fragments of the prismatic bed of inoceramid shells; other grains: q—quartz; gl—glauconite. All photographs were taken in unpolarized light on an Olympus-BX43 microscope with an Olympus-DP71 camera at the Moscow State University Shared Use Center. Scale bar 200 μm.



which distinguishes this specimen from a typical representative. C. dariensis is the index species of the same inoceramid zone as described above: *Sphaeroceramus sarumensis–Cataceramus dariensis*, and has the same stratigraphic distribution (Walaszczyk, 1997).

Thus, finds of Sphaeroceramus cf. sarumensis and Cataceramus sp. ex gr. C. dariensis characterize the Sphaeroceramus sarumensis-Cataceramus dariensis Zone, at the top of which the lower-upper Campanian boundary is drawn (Walaszczyk et al., 2016). The zone is correlated with the two foraminiferal zones Bolivinoides granulatus [=B. pustulata]–Stensioeina gracilis and Bolivinoides decoratus (Walaszczyk et al., 2016), equivalents of which are also established in the section under consideration (see below), or with the interval between the middle of the Offaster pilula Zone (middle of the lower Campanian) and the Gonioteuthis quadrata gracilis/Belemnitella mucronata Zone (upper part of the lower Campanian) (Jagt et al., 2004). Unfortunately, we do not know the exact position of these specimens in the section, but even if we knew, it would still be impossible to outline the position of the top of the inoceramid zone under discussion and reliably record the lower-upper Campanian boundary. The remaining macrofossils from the Kudrino-1 section characterize a wide stratigraphic interval and do not specify the age of the deposits; however, belemnites were found in the nearby Kudrino-3 section.

Rostra of *Belemnitella mucronata* (v. Schlotheim) found in the lower six meters of Submember XIXb of the neighboring Kudrino-3 section (Pl. II, figs. 1, 2) biostratigraphically significant. These are are medium-sized rostra (postalveolar distance 55 mm (specimen 149/4) and 49.2 mm (specimen 149/5), aspect ratio 3.9 (specimen 149/4) and 3.05 (specimen 149/5)); Shatsky index 12 mm (specimen 149/4) and 8 mm (specimen 149/5); slits angle 10 (specimen 149/4) and 13 (specimen 149/5) (the terminology can be found in (Moskvin, 1959; Arkadyev and Bogdanova, 1997)). Low-relief imprints of vessels are visible on the weathered surface of the rostra. Due to the limited number of specimens, it is difficult to identify the subspecies. However, these findings are important because the species B. mucronata is a zonal index of the lower part of the upper Campanian of Western Europe (Keutgen, 2011).

Similar rostra are described from the upper Campanian deposits of the Belbek River valley as *Belemnitella mucronata senior* (Nowak) (identifications by G.Ya. Krymgholts in (*Atlas melovoi fauny...*, 1997)). This subspecies was once included in the synonymy of the species *Belemnitella mucronata* s. str. (Christensen, 1986). Although D.P. Naidin did not agree with this synonymy, his lists of belemnites from the Crimean sections do not contain the subspecies *B. mucronata senior* (Iolkichev and Naidin, 1999), unlike *B. mucronata mucronata*. The rostra of *Belemnitella mucronata* that we found, come from the lower part of the upper Campanian, which is quite consistent with the interpretation of D.P. Naidin (Iolkichev and Naidin, 1999.

All belemnite rostra are covered with borings of varying intensity, interpreted as channels formed by (?) algae or the foraminifer *Dendrina* (Morris) (Pl. II, fig. 6), (?) phoronids *Talpina ramosa* von Hagenow (Pl. II, fig. 7), (?) fungi or sponges *Calcideletrix flexuosa* Mägdefrau (Pl. II, fig. 8). Notably, finds of *Dendrina* suggest poorly lit or entirely dark environment (Bromley, 2004). The fact that drillings cover the entire surface of some rostra indicates a prolonged presence of the latter on the substrate surface and, apparently, a decrease in the depositional rate in the interval corresponding to Submember XIXb.

# Foraminifers

For the Kudrino-1 section, data on the distribution of foraminifers have been obtained. Information on benthic foraminifers was obtained for the entire section (locality 3169) and is published here for the first time. Data on planktonic foraminifers were obtained by L.F. Kopaevich (MSU) based on 17 samples collected from the lower 24 m of the section (locality 2414), and published by her earlier (Kopaevich and Khotylev, 2014; Kopaevich and Vishnevskaya, 2016). They form the basis for writing the corresponding part of the paper with some changes and additions. Noteworthy that the position of the samples of locality 2414 (Figs. 3, 4) has been refined in comparison with that given by Kopaevich and Vishnevskaya (2016).

**Planktonic foraminifers (PF).** The lower-upper Campanian boundary beds in Crimea have not yet been sufficiently studied for the distribution of PF, therefore there are different points of view on the zonal biostratigraphy of PF in this interval. We adopted the "standard" Mediterranean scale (Robaszynski and Caron, 1995) as the basis for the zonal sequence, supplementing it with data from the Crimean sections, as discussed below.

Plate II. Finds of macrofauna and traces of bioerosion. (1, 2) *Belemnitella mucronata* (v. Schlotheim): (1) specimen MZ MSU no. 149-4, (2) specimen MZ MSU no. 149-5; (a) dorsal view, (b) lateral view, (c) ventral view, (d) dorso-ventral split view; (3) *Pachydiscus (Pachydiscus) launayi* (De Grossouvre), specimen no. MZ MSU 149-1, lateral view; (4) *Sphaeroceramus* cf. *sarumensis* (Woods, 1912), specimen MZ MSU no. 149-2: (a) right valve, (b) right valve in anterior margin view; (5) *Cataceramus* sp. ex gr. *dariensis* (Dobrov et Pavlova), specimen MZ MSU no. 149-3, upper view; (6) *Dendrina dendrina* (Morris, 1851) on a rostrum of *Belemnitella mucronata*, specimen MZ MSU no. 149-4; (7) *Talpina ramosa* von Hagenow, 1840 on a rostrum of *Belemnitella sp.*, specimen MZ MSU no. 149-6; (8) *Calcideletrix flexuosa* Mägdefrau, 1937, specimen MZ MSU no. 149-6. The specimens come from scree on Submember XVIIc, (1, 2, 6–8), upper Campanian, Kudrino-3 section and XVIIIa (3–5), lower Campanian, Kudrino-1 section).



STRATIGRAPHY AND GEOLOGICAL CORRELATION Vol. 32 No. 2 2024

![](_page_9_Figure_1.jpeg)

**Fig. 4.** Distribution of planktonic foraminifers in the studied section, locality 2414 (2002) (according to Kopaevich and Vishnevskaya, 2016, with modifications and corrected position of samples). For legend, see Fig. 1.

Based on many years of research by Maslakova (1977) established two zones in the Crimean Campanian: Globotruncanita elevata Zone in the lower Campanian and Globotruncana morozovae Zone in the upper Campanian. The Globotruncanita elevata Zone was defined by an index species, "common in a given zone and known in overlying deposits," and the Globotruncana morozovae Zone was recognized by an index species, "the distribution of which, corresponding to the stages of its early evolution and abundance, was limited to this zone" (i.e., it appeared earlier) (Maslakova, 1977, p. 87).

Alekseev (1989), following Maslakova (1977), assigned lower Campanian Members XVI–XVIII to the Globotruncanita elevata Zone, and the upper Campanian Member XIX to the Globotruncana morozovae Zone (=Contusotruncana morozovae (Vasilenko) in modern nomenclature).

Kopaevich (2010) identified in the Campanian of the Crimean-Caucasian region a zone of partial distri-

bution of Globotruncanita elevata in the lower Campanian and two interval zones in the upper Campanian: Globigerinelloides multispinus and Contusotruncana morozovae.

The base of the G. elevata Zone is recorded by L.F. Kopaevich by the presence of a zonal species (without *Dicarinella asymetrica* (Sigal)) and by the appearance of *Globotruncana arca* (Cushman). The species *Globotruncanita elevata* (Brotzen) appears somewhat earlier and is distributed together with the last *D. asymetrica*.

The first *G. elevata* in the Kudrino-2 section were found together with *G. arca* in the interval of samples 3184/20-3184/40 (middle of Submember XVIa3–Submember XVId) (Guzhikov et al., 2021a), and in the Aksu-Dere section (locality 3168) the index species was not found and the Globotruncana arca/Globotruncanita elevata Zone was established based on the distribution of *G. arca*.

In the Kudrino-1 section, we recognize the Globotruncanita elevata Zone (samples 2414/1–2414/11, Submember XVId1-lower half of Member XVII; Fig. 4). The base of the zone in this section is unknown, but perhaps should be outlined according to sample 3184/40 in the Kudrino-2 section (see above). The top is defined by the appearance of *Globotruncana* ventricosa (see below). The base of the Globigerinelloides multispinus and Contusotruncana morozovae zones is drawn by L.F. Kopaevich on the appearance of zonal species, although the index species themselves are also found in vounger deposits. In the original interpretation in the sections of the Vistula River (Poland), the base of the G. multispinus Zone is defined by the appearance of the index species itself from the base of the upper Campanian, and the top is defined by the appearance of the Early Maastrichtian index species Rugoglobigerina pennyi Bronnimann (Peryt, 1980).

The G. multispinus Zone was placed by Kopaevich (2010) into a zonal sequence instead of the Globotruncana ventricosa Zone (Robaszynski and Caron, 1995) on the basis that the latter index species does not have well-defined morphological characters and its appearance is diachronic in different regions (Petrizzo et al., 2011). The level of appearance of *Globigerinelloides multispinus* (Lalicker) is established in the Kudrino-1 section, where it falls in the middle of Member XVII (sample 2414/11; Kopaevich and Vishnevskaya, 2016) of the lower Campanian, but here is the exact level of appearance of *Contusotruncana morozovae* and the vertical distribution of *G. multispinus* in the Kudrino–Aksu-Dere sections remain insufficiently studied.

It is worth emphasizing that the species *G. multisp-inus* appears here in the lower and not the upper Campanian. The same species was recorded in one sample of the Alan-Kyr section, in the upper Campanian Globotruncanella havanensis Zone (Ovechkina et al., 2021). From here it is obvious that the stratigraphic

volume of the G. multispinus Zone in Crimea (as interpreted by L.F. Kopaevich), although not precisely determined, is obviously different from sections from the stratotype area of this zone in Poland. For this reason, the thesis about the lesser diachrony of *G. multispinus* is clearly exaggerated.

In the upper part of the Aksu-Dere section (member XVII, sample interval 3168/60–3168/66) above the Globotruncana arca/Globotruncanita elevata Zone, L.F. Kopaevich established the Globotruncana ventricosa Zone (in Guzhikov et al., 2021a, p. 36), although the first finds of *G. ventricosa* are more ancient and come from sample 3168/55. According to Maslakova (1977), the species *Globotruncana ventricosa* White ranges in Crimea from the upper Santonian to the upper Campanian.

Recent studies of the Santonian-Campanian interval indicate the distribution of *G. ventricosa* only in the Campanian of Crimea (Guzhikov et al., 2021a; Ovechkina et al., 2021), including in the Alan-Kyr section, where the Globotruncana plummerae/Globotruncanita ventricosa Zone, assigned to the lower Campanian, is located within the interval of direct polarity C33n (according to this work, this is already the upper Campanian). The Alan-Kyr section also contains *Contusotruncana morozovae*, appearing 2 m above the base of the G. plummerae/G. ventricosa Zone, almost at the lower-upper Campanian boundary based on nannoplankton (Ovechkina et al., 2021).

From the above it follows that Globotruncana ventricosa is found much more frequently in Crimean sections than G. multispinus, and the diachrony of its boundaries is comparable to the diachrony of the boundaries of other foraminiferal zones. Taking into account that the G. ventricosa Zone is present in the Upper Cretaceous stratigraphic scale of the East European Platform (EEP) (Olfer'ev and Alekseev, 2003) and in the General stratigraphic scale (Olfer'ev and Alekseev, 2002), Globotruncana ventricosa is a "more convenient" index-species compared to G. multispinus, although it less reliability identifiable. For these reasons, in the Kudrino-1 section we recognize the Globotruncana ventricosa Zone, and not the G. multispinus Zone (as in Kopaevich and Vishnevskaya, 2016). It is established in the interval of samples 2414/12-2414/17 (upper half of the lower Campanian Member XVII-lower half of Submember XVIIIa) by the first presence of a zonal form, but perhaps extends higher.

The PF assemblages of the higher interval of the upper Campanian, starting from the base of Submember XIXa, have not been studied, and we, somewhat tentatively, following Maslakova (1977) and Alekseev (1989), attribute this interval to the upper Campanian **Contusotruncana morozovae Zone.** 

**Benthic foraminifers (BF).** Tests of benthic foraminifers from the Kudrino-1 section were isolated from 25 samples using acetolysis with glacial acetic acid. The study of the morphology of foraminiferal tests and their selection for the collection was carried out using a Bresser Advance ICD optical microscope. Photographs of foraminifers were taken using a Tescan MIRA 2 LMU field emission scanning electron microscope in the Laboratory for Diagnostics of Nanomaterials and Structures of N.G. Chernyshevsky Saratov State University.

Identifications were made using the BF taxonomy database at the World Register of Marine Species platform https://www.marinespecies.org/foraminifers (Hayward et al., 2022), based on the works of Loeblich and Tappan (1987, 1992). The correlation of bioevents in the BP of different regions of the European Paleobiogeographical Region (EPR) took into account local zonal schemes (Koch, 1977; Hart et al., 1989; King et al., 1989; Schönfeld, 1990; Gawor-Biedowa, 1992; Beniamovsky, 2008; Walaszczyk et al., 2016; Vishnevskaya et al., 2018) and a monographic study of representatives of the family Bolivinoididae Loeblich et Tappan (Georgescu, 2018).

The first data on the composition of BF communities for the Kudrino-1 section are presented in (Nikishin et al., 2013; Kopaevich and Khotylev, 2014), where *Gavelinella stelligera* (Marie), *G. clementiana* (d'Orb.), *Cibicides voltzianus* (d'Orb.), which allowed these authors to establish the LC14b Subzone (Beniamovsky, 2008) and suggest a Middle Campanian age of the host deposits for a tripartite division of the Campanian.

In this study, 39 species of BFs were identified and, based on their vertical distribution, six units were recognized in the rank of Beds with fauna (Fig. 5). They were assigned BFK indices (Benthic Foraminifera of Kudrino), by analogy with the previously identified indices of units in the Kudrino-2 section (Guzhikov et al., 2021a, 2021b), the numbering of which was continued, and the sections themselves were correlated both with each other and with the Aksu-Dere section (Fig. 6). Thus, in the Kudrino-1 section, Beds with BFK-4 and BFK-5, established previously, have been identified, and Beds with BFK-6, BFK-7, BFK-8 and BFK-9 have been proposed for the first time. Index taxa from identified BFs are shown in Pls. III and IV.

Beds with Pseudogavelinella clementiana clementiana (BFK-4) were recognized in the sample interval 3169/1–3169/10 (Submember XVId1–XVId2) by the constant presence of the index subspecies Pseudogavelinella clementiana clementiana (d'Orbigny) and of the characteristic assemblage Hagenowella obesa (Reuss), Ammodiscus cretaceous (Reuss), Ataxophragmium crassum (d'Orbigny), Globorotalites michelinianus (d'Orbigny), Globorotalites cf. emdyensis Vassilenko, Gavelinella costulata (Marie), Stensioeina pommerana Brotzen, S. gracilis (Marsson), Gyroidina turgida (Hagenow), Eponides frankei Brotzen, Neoflabellina gibbera (Wedekind), Gavelinella pertusa (Marsson), Osangularia cordieriana (d'Orbigny), Cibicides ribbingae Brotzen, C. eriksdalensis (Brotzen), Eouvigerina cretae (Ehrenberg), Bolivinoides culverensis Barr, B. strigillata (Chapman), Gavelinella stelligera (Marie), Reussella szajnochae (Grzybowski), occasional Neoflabellina sphenoidalis (Wedekind).

The subspecies P. clementiana clementiana is widespread in the Campanian of the European Paleobiogeographic Region (EPR), but its first appearance is recorded both in the lower Campanian (Schönfeld, 1990; Beniamovsky, 2008; Walaszczyk et al., 2016) and in the terminal Santonian (Maslakova, 1959; Gawor-Biedowa, 1992; Magniez-Jannin, 1995). V.N. Beniamovsky, in his scheme of zonal division of the Upper Cretaceous deposits of the EEP according to benthic foraminifers, connected the level of appearance of *P. clementiana clementiana* with the beginning of the "pseudo-Gavelinella" stage of the development of the BF and compared this event with the base of the Campanian (Beniamovsky, 2008). The Pseudogavelinella clementiana clementiana LC12 Zone proposed in this scheme, based on the results of the correlation of EEP zonal schemes (Vishnevskaya et al., 2018), corresponds to the upper (Campanian) part of the nannoplankton CC17 Zone, which occupies a boundary position between the Santonian and Campanian in the International Stratigraphic Scale (ISC) (Gradstein et al., 2020). In general, despite the debatable level of the first appearance of the index species, the BF complex identified in submembers XVId1-XVId2 allows us to date the age of the deposits as the Early Campanian. A similar BF assemblage was identified in the Aksu-Dere section (Guzhikov et al., 2021a) under the abbreviation BFAD-5, BFAD-6.

*Beds with Bolivinoides pustulata* (BFK-5) are recognized in the sample interval 3169/20–3169/24 (Member XVII) based on the first presence of the index species *Bolivinoides pustulata* Reiss. The assemblage contains a few *Spiroplectammina lingua* Akimetz; at the top of the member, sample 3169/24 contained *Heterostomella foveolata* (Marsson), *H. rugosa* (d'Orbigny), and

Cibicides involutus (Reuss). The upper part of the Beds (samples 3169/20, 3169/24) is characterized by a high number of calcispheres and the disappearance of B. strigillata and C. eriksdalensis. The first appearance of the species *B. pustulata*, which was previously identified as B. granulatus (Hofker) (Guzhikov et al., 2021a), is recorded in the middle–upper parts of the lower Campanian of the EPR (Gawor-Biedowa, 1992; Magniez-Jannin, 1995). In sections of England and North-West Germany, its appearance was recorded within the Galeola senonensis Zone (Swiecicki, 1980; Schönfeld, 1990), and in the Carpathian region-at the base of the Sphaeroceramus sarumensis-Cataceramus dariensis Zone (Walaszczyk et al., 2016), equivalents of which are also present in the Kudrino-1 section (see above). According to deep-sea drilling data (Georgescu, 2018), the first appearance of *B. pustulata* was identified in the upper part of the Heterohelix reussi Zone, which corresponds to the lower part of the Gonioteuthis quadrata belemnite Zone (Ogg et al., 2004). Therefore, the age of Unit XVII is determined to be the second half of the Early Campanian. Previously, a similar BF assemblage was identified in the Aksu-Dere section (Guzhikov et al., 2021a) with the abbreviation BFAD-7.

Beds with Bolivinoides decorata (BFK-6) were recognized in the sample interval 3169/25–3169/54 (Submember XVIIIa–lower part of Submember XIXa) based on the first presence of the index species Bolivinoides decorata (Jones). Here the composition of the BF assemblage is updated due to the appearance of Spiroplectammina rosula (Ehrenberg), Heterostomella foveolata, H. rugosa, Loxostomum eleyi (Cushman), Cibicides involutus. The disappearance of Bolivinoides culverensis is recorded at the top of the beds. The first appearance of the species B. decorata can be traced throughout the EPR in the lower Campanian (Koch, 1977; Gawor-Biedowa, 1992) and reflects the beginning of the Lamino-Voloshinovella-Cybisidoides stage of development of BF in the EEP (Beniamovsky,

Plate III. Benthic foraminifers from the Kudrino-1 section. (1) Bolivinoides strigillata (Chapman), Sample 3169/20, specimen SSU IPR no. 263/3169-20-14; (2) Bolivinoides strigillata (Chapman), Sample 3169/10, specimen SSU IPR no. 263/3169-10-26; (3) Bolivinoides culverensis Barr, Sample 3169/10, specimen SSU IPR no. 263/3169-10-25; (4) Bolivinoides pustulata Reuss, Sample 3169/20, specimen SSU IPR no. 263/3169-20-15; (5) Bolivinoides pustulata Reuss, Sample 3169/20, specimen SSU IPR no. 263/3169-20-27; (6) Trachelinella watersi (Cushman), Sample 3169/60, specimen SSU IPR no. 263/3169-60-45; (7) Bolivinoides decorata (Jones), Sample 3169/30, specimen SSU IPR no. 263/3169-30-33; (8) Bolivinoides decorata (Jones), Sample 3169/55, specimen SSU IPR no. 263/3169-55-41; (9) Bolivinoides delicatula Cushman, Sample 3169/60, specimen SSU IPR no. 263/3169-60-46; (10) Bolivinoides peterssoni Brotzen, Sample 3169/87, specimen SSU IPR no. 263/3169-87-96; (11) Bolivinoides peterssoni Brotzen, Sample 3169/92, specimen SSU IPR no. 263/3169-92-93; (12) Bolivinoides peterssoni Brotzen, Sample 3169/100, specimen SSU IPR no. 263/3169-100-12; (13) Swiecickina clavata (Plotnikova), Sample 3169/100, specimen SSU IPR no. 263/3169-100-65; (14) Bolivina witwickae Gawor-Biedowa, Sample 3169/100, specimen SSU IPR no. 263/3169-100-67; (15) Reussella szajnochae (Grzybowski), Sample 3169/55, specimen SSU IPR no. 263/3169-55-24; (16) Loxostomum elevi (Cushman), Sample 3169/20, specimen SSU IPR no. 263/3169-20-16; (17) Spiroplectammina lingua Akimetz, Sample 3169/20, specimen SSU IPR no. 263/3169-20-28; (18) Spiroplectoides rosula (Ehrenberg), Sample 3169/25, specimen SSU IPR no. 263/3169-25-29; (19) Heterostomella foveolata (Marsson), Sample 3169/25, specimen SSU IPR no. 263/3169-25-31; (20) Eouvigerina cretae (Ehrenberg), Sample 3169/55, specimen SSU IPR no. 263/3169-55-99; (21) Neoflabellina sphenoidalis (Wedekind), Sample 3169/83, specimen SSU IPR no. 263/3169-83-78; (22) Neoflabellina gibbera (Wedekind), Sample 3169/30, specimen SSU IPR no. 263/3169-30-32; (23) Spiroplectoides rosula (Ehrenberg), Sample 3169/30, specimen SSU IPR no. 263/3169-30-34; (24) Hagenowella obesa (Reuss), Sample 3169/50, specimen SSU IPR no. 263/3169-50-38; (25) Coryphostoma cf. plaitum (Carsey), Sample 3169/100, specimen SSU IPR no. 263/3169-100-68: (a) ventral view, (b) peripheral view, (d) dorsal view. Scale bar 100 µm.

![](_page_12_Figure_1.jpeg)

2008). Correlation with the nannoplankton zonal scheme allowed correlation of this event with the upper part of the CC17 Zone across the EEP (Vishnevskaya et al., 2018). However, the presence of *Cibicides involutus* [=*C. aktulagayensis* Vasilenko] suggests correlation of the BFK-6 Beds with the upper part of the LC13 Zone (Beniamovsky, 2008), which is correlated with the CC18 Zone and the base of the nannoplankton CC19 Zone (Vishnevskaya et al., 2018).

According to Georgescu (2018), B. decorata appears at the base of the Belemnitella mucronata belemnite Zone, which was previously associated with the base of the Middle Campanian (Ogg et al., 2004). A similar distribution of the species has been established in South England (Hart et al., 1989). At the same time, Walaszczyk et al. (2016) studying the Carpathian region, recorded the appearance of decorata below the "Inoceramus" azerbaydjanensis-"Inoceramus" vorhelmensis Zone, which correlates with the 'Inoceramus' azerbaydianensis MSH Zone (Gradstein et al., 2020), within which the Lower-Middle Campanian boundary of the American scale is drawn (Gradstein et al., 2012). Therefore, this interval is proposed to be assigned to the upper part of the lower Campanian.

Beds with Brotzenella monterelensis, Cibicides voltziana (BFK-7) established in the sample interval 3169/55-3169/58 (lower part of Submember XIXa) by the simultaneous appearance of the index species Brotzenella monterelensis (Marie), Cibicides voltziana (d'Orbigny), which corresponds to the onset of the Brotzenella stage of development of BF (Beniamovsky, 2008). From the same level, the appearance and constant presence of Gavelinella beccariiformis (White) and Angulogavelinella aff. gracilis (Marsson) is recorded, more typical of the terminal Campanian. *B. pustulata* disappears in the upper part of the Beds; The species identified in the underlying beds continue to occur at this level. It should be noted that in washed samples (but not in thin sections) of sample 3169/55 there is an increased content of siliceous material,

which is associated with partial or complete replacement of foraminiferal chambers with silica.

Appearance of *Br. monterelensis* and *C. voltziana* in the zonal scheme of V.N. Beniamovsky's BF for the EEP (Beniamovsky, 2008) indicates the base of both the LC14 Zone and its upper LC14b Subzone, the position of which corresponds to the lower part of the upper Campanian of the GSS (Vishnevskaya et al., 2018). The simultaneous appearance of these index species in the Kudrino-1 section may indicate the likelihood of a gap equaling the range of the LC14a Subzone, but this needs to be verified using other data.

It is known that the level of occurrence of B. monterelensis correlates with the base of the Hoplitoplancoesfeldiensis-Belemnitella mucronata ceticeras mucronata Zone, the base of which corresponds to the lower boundary of the Middle Campanian (Kopaevich et al., 1999; Beniamovsky and Kopaevich, 2001; Baraboshkin et al., 2013). In South England, the base of the Gavelinella monterelensis/G. usakensis UKB.17 Zone also corresponds to the base of the B. mucronata Zone (Hart et al., 1989). A detailed study of the nature of the distribution of belemnites and echinoderms at the boundary of the lower and upper Campanian in southern Poland and northern Germany (Jagt et al., 2004) showed that the base of the upper Campanian (with a bipartite subdivision of the stage) is located above the level of appearance of B. mucronata (Figs. 6, 7). It is precisely at this boundary that the joint appearance of C. voltziana and Br. monterelensis in the Carpathian region is recorded (Walaszczyk et al., 2016).

The above allows us to conclude that the BFK-7 Beds can be attributed to the base of the upper Campanian.

**Beds with** *Bolivinoides delicatula* (BFK-8) are recognized in the sample interval 3169/60–3169/83 (middle part of Submember XIXa) by the appearance of the index species *Bolivinoides delicatula* (Cushman). Up the section there is a constant presence of *Neoflabellina suturalis suturalis* (Cushman).

Plate IV. Benthic foraminifera from the Kudrino-1 section. (1) Stensioeina pommerana Brotzen), Sample 3169/1, specimen SSU IPR no. 263/3169-1-1; (2) Stensioeina gracilis Brotzen, Sample 3169/1, specimen SSU IPR no. 263/3169-1-2; (3) Osangularia cordieriana (d'Orbigny), Sample 3169/1, specimen SSU IPR no. 263/3169-1-4; (4) Pseudogavelinella clementiana clementiana (d'Orbigny), Sample 3169/25, specimen SSU IPR no. 263/3169-25-19; (5) Cibicidoides aktulagayensis Vasilenko, Sample 3169/25, specimen SSU IPR no. 263/3169-25-20; (6) Cibicidoides eriksdalensis (Brotzen), Sample 3169/24, specimen SSU IPR no. 263/3169-24-81; (7) Eponides frankei Brotzen, Sample 3169/1, specimen SSU IPR no. 263/3169-35-76; (8) Gavelinella pertusa (Marsson), Sample 3169/65, specimen SSU IPR no. 263/3169-65-50; (9) Cibicides voltziana (d'Orbigny), Sample 3169/55, specimen SSU IPR no. 263/3169-55-23; (10) Brotzenella monterelensis (Marie), Sample 3169/55, specimen SSU IPR no. 263/3169-55-86; (11) Stensioeina beccariiformis (White), Sample 3169/55, specimen SSU IPR no. 263/3169-55-40; (12) Stensioeina beccariiformis (White), Sample 90, specimen SSU IPR no. 263/3169-90-60; (13) Globorotalites cf. emdyensis Vasilenko, Sample 3169/70, specimen SSU IPR no. 263/3169-70-74; (14) Globorotalites cf. emdyensis Vasilenko, Sample 3169/70, specimen SSU IPR no. 263/3169-70-72; (15) Globorotalites cf. emdyensis Vasilenko, Sample 3169/70, specimen SSU IPR no. 263/3169-70-73; (16) Angulogavelinella aff. gracilis (Marsson), Sample 3169/55, specimen SSU IPR no. 263/3169-55-42; (17) Angulogavelinella aff. gracilis (Marsson), Sample 3169/70, specimen SSU IPR no. 263/3169-70-53; (18) Stensioeina pommerana Brotzen), Sample 3169/65, specimen SSU IPR no. 263/3169-65-89; (19) Globorotalites michelinianus (d'Orbigny), Sample 3169/65, specimen SSU IPR no. 263/3169-65-52; (20) Pseudogavelinella clementiana laevigata (Marie), Sample 3169/92, specimen SSU IPR no. 263/3169-92-92; (21) Pseudogavelinella clementiana laevigata (Marie), Sample 3169/90, specimen SSU IPR no. 263/3169-90-63; (22) Pseudogavelinella clementiana laevigata (Marie), specimen SSU IPR no. 263/3169-90-63. (a) Ventral view, (b) peripheral view, (c) dorsal view. Scale bar  $100 \,\mu m$ .

![](_page_14_Figure_1.jpeg)

## BARABOSHKIN et al.

![](_page_15_Figure_1.jpeg)

Fig. 5. Distribution of benthic foraminiferal species in the Kudrino-1 section.

STRATIGRAPHY AND GEOLOGICAL CORRELATION Vol. 32 No. 2 2024

![](_page_16_Figure_1.jpeg)

![](_page_16_Figure_2.jpeg)

![](_page_17_Figure_1.jpeg)

![](_page_17_Figure_2.jpeg)

STRATIGRAPHY AND GEOLOGICAL CORRELATION Vol. 32 No. 2 2024

The species *B. delicatula* in Crimea was previously described by Maslakova (1959) from Maastrichtian-Danian deposits as Bolivinoides delicatulus (Cushman). According to the results of a revision of the taxonomy and stratigraphic distribution of the species (Georgescu, 2018), the level of its occurrence corresponds to the upper part of the B. mucronata Zone (upper part of the middle Campanian-lower part of the upper Campanian). M.D. Georgescu uses B. deli*catula* as an index species for the eponymous zone, the upper limit of which is established by the appearance of Bolivinoides miliaris Hiltermann et Koch. The latter was not found in the Kudrino-1 section, which may indicate the absence of the upper part of the upper Campanian in it. In the Carpathian region, the presence of Bolivinoides sidestrandensis Barr (Walaszczyk et al., 2016), reidentified as *B. delicatula* (Georgescu, 2018), is recorded in the upper part of the middle Campanian (B. langei and "Inoceramus" tenuilineatus zones). In the studied sections in the area of the village of Kudrino, rostra of Belemnitella mucronata are found slightly higher in the section. This suggests a certain diachronicity of the BF levels under consideration. Within the EEP, Beniamovsky (2008), recorded the characteristic presence of the species *B. delicatula* for LC18 Zone, which corresponds to the upper part of the nannoplanktonic CC22b Zone (Vishnevskaya et al., 2018), corresponding to the upper substage of the Campanian (Gradstein et al., 2012). The level of disappearance of *B. pustulata* at the base of the BFK-8 Beds can be traced in the EPR in the upper part of the Campanian (Magniez-Jannin, 1995). Thus, the Beds with BFK-8 belong to the lower part of the upper Campanian. The duration of a small gap established on the basis of thin section 3169/82 (Pl. I, fig. e) showing sharp enrichment of marls with terrigenous admixtures cannot be determined.

Beds with *Bolivinoides peterssoni* (BFK-9) are recognized in the sample interval 3169/87–3169/100 (upper part of Submember XIXa) by the appearance of the index species *Bolivinoides peterssoni* Brotzen. The assemblage is also supplemented by *Pseudogavelinella clementiana laevigata* (Marie) (=*Gavelinella annae* (Pozaryzska)?), *Swiecickina clavata* (Plotnikova), *Bolivina witwickae* Gawor-Biedowa and *Coryphostoma* cf. *plaitum* (Carsey), although the species first found below this level continue to dominate. The last find of *B. delicatula* was established at sample level 3169/90.

The most stratigraphically significant species is *B. peterssoni*, an index species of the zonal schemes of various EPR regions. In Northwestern Germany, the appearance of *B. peterssoni* corresponds to the upper part of the grimmensis/granulosus Zone (upper Campanian) (Schönfeld, 1990), and in southern England it corresponds to the base of the lanceolata Zone (Hart et al., 1989), which, with the current understanding of the Campanian–Maastrichtian boundary (Odin and Lamaurelle, 2001) also corresponds to the upper Campanian.

These and other data were used in the revision of the family Bolivinoididae Loeblich et Tappan published by Georgescu (2018). According to the identified succession of species, the level of occurrence of B. peterssoni is located within the Belemnitella lanceolata Zone, and the level of appearance of another index species, Swiecickina clavata, coincides with the base of the lanceolata Zone. The species B. witwickae, for the first time recorded in Crimea, was previously known only from the upper Campanian and Maastrichtian (Lublin Chalk) of Eastern Poland (Gawor-Biedowa, 1992). Consequently, Beds BFK-9 belong to the upper Campanian. At the same time, sequence of species of the genus Bolivinoides substantiated by Georgescu (2018) suggests that the terminal part of the Campanian is absent in the Kudrino-1 section, since the event of the first appearance of *Bolivinoides austra*lis Edg. was not recorded here, while the B. miliaris Zone was determined only from indirect evidence (the appearance of *B. peterssoni*) and is not confirmed by the presence of the index species (Fig. 7). In addition, the presence of an important marker taxon of the upper part of the upper Campanian, Coryphostoma incrassata (Reuss), an index species of the LC16 Zone of Beniamovsky's scheme (2008), corresponding to the lower part of the nannoplankton CC22b Zone (Vishnevskaya et al., 2018), was not revealed. These contradictions can only be explained by diachrony: the appearance of B. peterssoni, S. clavata, and Bolivina witwickae in the South-Western Crimea occurs earlier than in other regions of the EPR, especially since the first Belemnitella mucronata were found in a higher part of the section. Thus, in the Kudrino-1 section, benthic foraminifers indicate Beds with assemblages characteristic of the lower Campanian (BFK-3-BFK-6) and upper Campanian (BFK-7-BFK-9). The BF assemblage, characteristic of the middle Campanian of the American scale, in accordance with data on the Carpathian region (Walaszczyk et al., 2016), is proposed to be distinguished according to the level of appearance of *Gavelinella annae* (Pozayzska), which is probably synonymous with the subspecies Pseudogavelinella clementiana laevigata (Marie), the level of appearance of which in the Kudrino-1 section is recorded in the upper part of Submember XIXa in sample 3169/92 (Fig. 7).

#### Nannoplankton

Twenty-two samples were analyzed for nannoplankton, including a sample from the bentonite clays. The preparations were prepared according to standard methods (Bown and Young, 1998) and studied under a BiOptic200 light polarizing microscope in transmitted light and crossed nicols at a magnification of 1000x. Photographs were taken using a Canon EOS 550D digital camera and a Canon photo attachment. The relative abundance of certain species was estimated from counts in 100 consecutive fields of view on

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a randomly selected area of the preparation. Species diversity was assessed for the entire specimen, the area of which was  $24 \times 24$  mm on a glass slide. The preservation of the nannofossils is average, with minor secondary recrystallization; the main diagnostic features are preserved. Microresidues were present in all samples. The assemblage of calcareous nannoplankton from the Campanian of the Kudrino-1 section includes 46 species assigned to 25 genera (Fig. 8).

Calcareous nannoplankton of the Campanian Stage of the Mountainous and Plain Crimea was studied by Shumenko and Stetsenko (1978) and Matveev (2015). New information on this interval in Southwestern Crimea was obtained in 2021 when studying the Aksu-Dere and Kudrino-2 sections (Guzhikov et al., 2021a).

Currently, two nannoplankton biostratigraphic scales are used for the Upper Cretaceous. One of them was developed by Burnett (1998), the other by Sissingh (1977) and improved by Perch-Nielsen (1985). These scales compare well with each other (Gradstein et al., 2020). For the biostratigraphic division of the Campanian Kudrino-1, the J. Barnett scale was used, as it is more fractional.

Compared to coeval assemblages of the section of the village of Maloe Sadovoe (southern and southwestern slopes of Mount Arman-Kaya (Matveev, 2015)) there is a decrease in species diversity. The presence in the section of such taxa as *Reinhardtites* levis Prins et Sissingh in Sissingh, 1977, Reinhardtites anthophorus (Deflandre, 1959) Perch-Nielsen, 1968. Broinsonia parca parca (Stradner, 1963) Bukry, 1969, Broinsonia parca constrica Hattner et Wise, 1980 (Pl. V, Fig. 26) suggests the undivided zones UC14d–UC15d (Burnett, 1998). Reinhardtites levis (Pl. V, fig. 4) is distributed in the lower Campanian-Maastrichtian interval (UC14d–UC18 zones of Burnett's (1998) scale. Broinsonia parca parca (Pl. V, fig. 27) is characteristic only of the Campanian (UC14–UC15d Zone of Burnett's (1998) scale). The boundary between zones UC14–UC15 is not defined, because it is drawn by the appearance of Misceomarginatus pleniporus Wind et Wise in Wise et Wind, 1977, which was not found in the Kudrino-1 section.

If only nannoplankton data are used, then the age of the host sediments should be interpreted as early Campanian, since the following species appearing in the upper Campanian were not found in the section: *Ceratolithoides aculeus* (Stradner, 1961) Prins et Sissingh in Sissingh, 1977, *Eiffellithus parallelus* Perch-Nielsen, 1973, *Uniplanarius sissinghii* (Perch-Nielsen, 1986) Farhan 1987, *U. trifidus* (Stradner in Stradner et Papp, 1961) Hattner et Wise in Wind et Wise, 1983. The species *Reinhardtites anthophorus* ranging from the Turonian to the UC15d Subzone (base of the upper Campanian) was represented in the section by a single specimen (Fig. 8). This conclusion is not confirmed by other groups of microfossils and other data. It is obvious that the general scarcity of the assemblage and the dissolution of nannoplankton during diagenesis do not allow an accurate conclusion about the age of the assemblage.

The sample of bentonite clays contained only one specimen of *Petrarhabdus copulatus* (Deflandre, 1959) Wind et Wise in Wise, 1983 (Pl. V, fig. 16), distributed from the Campanian to the lower Maastrichtian.

Regarding the relative abundance of nannofossils in each sample (Fig. 8), it is most variable in taxa such as Watznaueria barnesiae Pl. V, fig. 22), Watznaueria fossacincta, Lucianorhabdus cayeuxii (Pl. V, fig. 29) and, to a lesser extent, Micula staurophora (Pl. V, fig. 32). The number of specimens of nannoplankton species increases in the limestone interbeds in the visible base of Submember XVId1, in Submember XVId2 and in Member XVII. In the marly interbeds of these series, on the contrary, it decreases. In Submember XIXa, there is an increase in the number of specimens in the marl interbeds and a decrease in the clay marl interbeds. In the uppermost part of the section (sample 100, Fig. 8), the number of nannofossils sharply increases in the Bed of clayey marls. Increased numbers of Watznaue*ria* spp. indicates a relative increase in surface water temperature and oligotrophic conditions (Farouk et al., 2019). A low influx of nutrients is indicated by the presence of representatives of the genera *Eiffellithus*, *Prediscosphaera*, *Lithraphidites* (Mandur, 2016), and fluctuations in depths and temperatures are indicated by the ratio of cryophylic *Micula staurophora* and thermophilic Watznaueria barnesiae (Ovechkina and Alekseev, 2004). The abundance of the former species increases with increasing depth, while abundance of the second, on the contrary, increases with decreasing depth (Sanjary et al., 2019). However, representatives of the cryophilic genera Arkhangelskiella, Broinsonia, Prediscosphaera and the species Calculites obscurus (Deflandre, 1959) Prins et Sissingh in Sissingh, 1977 (Pl. V, fig. 31), Cribrosphaerella ehrenbergii (Arkhangelsky, 1912) Deflandre in Piveteau, 1952 (Pl. V, fig. 14), Eiffellithus eximius (Stover, 1966) Perch-Nielsen, 1968 (Pl. V, fig. 11) are found throughout the section represented by a few specimens (Fig. 8).

In general, the change in the abundance of nannofossils along the section reflects the instability of Campanian water masses in this part of the basin, characterized by a change in the mesotrophic/eutrophic regime with oligotrophic episodes, which was also established using foraminifers (Kopaevich and Vishnevskaya, 2016).

#### Calcareous Microproblematics

In two samples (3169/20 and 3169/24) from the upper part (5 m thick) of Member XVII in the Kudrino-1 section, *Gilianella* (calcareous microproblematics) were identified for the first time, character-

Thickness, m	Substage	Nannoplankton zones	Member/submember	Sample no., loc. 3169	فيلامنا مراجع مستقرقه مستحرانا والمليس	viangerovient cynnegormus versuma aarudosphaera bigelowii (Gran and Braarud)	oinsonia parca parca (Stradner) culites obscurus (Deflandre)	brosphaerella ehrenbergii (Arkhangelsky)	clagelosphaera reinhardtii (Perch-Nielsen) Romein	fellithus eximius (Stover)	cianorhabaus cayeuxu Denanure cianorhabdus maleformis Reinhardt	cula staurophora (Gardet)	crorhabdulus decoratus Deflandre	icozygus fibuliformis (Reinhardt)	idiscosphaera cretacea (Arkhangelsky) internation Inic Drine and Siscingh in Siscingh	<i>innurannes teris</i> Frins and Sissingn in Sissingn <i>iocansa crenulata</i> (Rramlette and Martini)	tecapsa ficula (Stover)	ttznaueria barnesiae (Black in Black and Barnes)	itznaueria biporta Bukry	ntznaueria Jossacincta (Black) trznaueria manivitiae Bukry	ugrha bdotus bicrescenticus (Stover)	ugrhabdotus embergeri (Noël)	<i>vinsonia parca constricta</i> Hattner et al.	cutum ellipticum (Gorka)	fellithus gorkae Reinhardt	iastozygus litterarius (Gorka)	<i>intapitaties carniolensis</i> Deflandre <i>iocansa anaustifurata</i> Rlack	inolithus orionatus (Reinhardt)						nure <i>cutum dissimilis</i> Wind and Wise in Wise and Wind	mivitella pemmatoidea (Deflandre in Manivit)	<i>indis</i> Perch–Nielsen <i>pous</i> (Bramlett and Martini) <i>i</i> Burnett
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Fig. 8. Distribution of nannoplankton in the Kudrino-1 section.

ized by distinct axial symmetry and tentatively attributed to calcareous dinocysts (Odin, 2008a, 2008b, 2011). The name of calcareous microproblematics "*Gilianella*" comes from the male name of Gilles, the author of this group, who described 60 species of these microproblematics from the Campanian-Maastrichtian deposits of France and Spain (Odin, 2009, 2011).

To extract calcareous microproblematics, we used the same method used for washing benthic foraminifer tests.

In sample 3169/20, 41 specimens of calcareous microproblematics were identified, among which the Late Campanian-Maastrichtian species *Aturella angulata* Odin (Pl. VI, figs. 8, 9) and *Scutellella crassa* Odin, Campanian *Azymella cannabinata* Odin (Table VI, figs. 11, 12) were identified to species, Late Campanian *Cimicellus nudatus* Odin (Pl. VI, fig. 6) and Corniculum sinuosum Odin (Pl. VI, fig. 7) (Odin, 2008a, 2008b).

Higher up the section in sample 3169/24, 57 specimens of calcareous microproblematics were identified, among which all the above-mentioned species continue to be present, including *Aturella angulata* Odin (Pl. VI, fig. 10). The species *Numismella tarbellica* Odin distributed in the late Campanian and Maastrichtian (Odin, 2008a, 2008b) appears (Pl. VI, fig. 13) and *Tubellus hunzikeri* (Odin) a taxon characteristic of the late Campanian (Odin, 2008b) becomes abundant (Pl. VI, figs. 1–5).

Thus, all species encountered are very close to the forms described from the narrow stratigraphic interval of the upper Campanian in the Tersis section in south-western France (Odin, 2008a, 2009) and from the Campanian Radotruncana calcarata Zone of the Navarra section in northern Spain, where the marker species of planktonic foraminifers are *Globotruncana elevata* and *G. ventricosa* (Odin, 2008b, 2011), also present in the Kudrino-1 section.

Similar forms are known from the upper Campanian Bostrychoceras polyplocum Zone of the Lägerdorf area in northwestern Germany (Bison et al., 2004; Wendler and Willems, 2004; Versteegh et al., 2009).

In the Kudrino-1 section, these microproblematics were found in Member XVII, at the very base of the Globotruncana ventricosa PF Zone and within the Beds with *Bolivinoides pustulata* along the SF of the upper part of the lower Campanian.

# Palynological Analysis

Material and methods. Twenty-one samples were studied (Fig. 9) from the Kudrino-1 section (locality 3169). Of these, 16 samples contained palynomorphs of satisfactory and poor preservation. Representative spectra were identified in the range of samples from 3169/20 to 3169/95, where palynomorphs are represented by numerous dinocysts, prasinophytes, at some levels together with spores and pollen of higher plants, and taxa of a certain systematic affiliation. Dinocyst assemblages from the Kudrino-1 section were compared with zonal assemblages from the Upper Cretaceous sections of England and Belgium, since dinocyst assemblages of Western Siberia (Lebedeva, 2006), Greenland (Nøhr-Hansen, 1996; Nøhr-Hansen et al., 2019), Norwegian and Barents seas (Radmacher et al., 2014, 2015) show either significant differences in their systematic composition or the presence of gaps in the succession, which makes their direct comparison impossible.

Changes in the composition of dinocyst associations made it possible to identify a succession of four dinocyst assemblages (DK—Kudrino dinocyst assemblages), established by the presence/appearance of stratigraphically important taxa and/or by certain quantitative characteristics of palynomorph assemblages. Their numbers continue the numbering of

Plate V. Nannoplankton from the Kudrino-1 section. (1) Ahmuellerella octoradiata (Górka, 1957) Reinhardt, 1966, Sample 3169/1; (2) Staurolithites laffittei Caratini, 1963, Sample 3169/90; (3) Tranolithus orionatus (Reinhardt, 1966a) Reinhardt, 1966b, Sample 3169/90; (4) Reinhardtites levis Prins et Sissingh in Sissingh, 1977, Sample 3169/85; (5) Zeugrhabdotus embergeri (Noël, 1959) Perch-Nielsen, 1984, Sample 3169/90; (6) Zeugrhabdotus bicrescenticus (Stover, 1966) Burnett in Gale et al., 1996, Sample 3169/55; 7 – Zeugrhabdotus diplogrammus (Deflandre in Deflandre et Fert, 1954) Burnett in Gale et al., 1996, Sample 3169/55; (8) Chiastozygus amphipons (Bramlette et Martini, 1964) Gartner, 1968, Sample 3169/90; (9) Chiastozygus litterarius (Górka, 1957) Manivit, 1971, Sample 3169/85; (10) Eiffellithus gorkae Reinhardt, 1965, Sample 3169/90; (11) Eiffellithus eximius (Stover, 1966) Perch-Nielsen, 1968, Sample 3169/90; (12) Placozygus fibuliformis (Reinhardt, 1964) Hoffmann, 1970, Sample 3169/85; (13) Cylindralithus serratus Bramlette et Martini, 1964, Sample 3169/55; (14) Cribrosphaerella ehrenbergii (Arkhangelsky, 1912) Deflandre in Piveteau, 1952, Sample 3169/90; (15) Biscutum ellipticum (Górka, 1957) Grün in Grün et Allemann, 1975, Sample 3169/90; (16) Petrarhabdus copulatus (Deflandre, 1959) Wind et Wise in Wise, 1983, Sample 3169/18; (17) Prediscosphaera cretacea (Arkhangelsky, 1912) Gartner, 1968, Sample 3169/85; (18) Retecapsa angustiforata Black, 1971, Sample 3169/85; (19) Retecapsa ficula (Stover, 1966) Burnett, 1997, Sample 3169/85; (20) Cyclagelosphaera reinhardtii (Perch-Nielsen, 1968) Romein, 1977, Sample 3169/85; (21) Watznaueria biporta Bukry, 1969, Sample 3169/90; (22) Watznaueria barnesiae (Black in Black et Barnes, 1959) Perch-Nielsen, 1968, Sample 3169/100; (23) Watznaueria manivitiae Bukry 1973, Sample 3169/10; (24) Arkhangelskiella cymbiformis Vekshina, 1959, Sample 3169/90; (25) Broinsonia parca *expansa* Wise et Watkins in Wise, 1983, Sample 3169/10; (26) *Broinsonia parca constricta* Hattner et al., 1980, Sample 3169/55; (27) *Broinsonia parca* (Stradner, 1963) Bukry, 1969, Sample 3169/85; (28) *Kamptnerius magnificus* Deflandre, 1959, Sample 3169/85; (29) Lucianorhabdus cayeuxii Deflandre, 1959, Sample 3169/90; (30) Lucianorhabdus maleformis Reinhardt, 1966, Sample 3169/90; (31) Calculites obscurus (Deflandre, 1959) Prins et Sissingh in Sissingh, 1977, Sample 3169/85; (32) Micula staurophora (Gardet, 1955) Stradner, 1963, Sample 3169/90. Photographs were taken using a light microscope with crossed nicols. Scale bar 2 µm.

![](_page_22_Figure_1.jpeg)

associations established previously in the Kudrino-2 section (Guzhikov et al., 2021a).

The stratigraphic distribution of dinocysts is shown in Figs. 9, 10, and index forms are shown in Pl. VII.

Assemblage with Eatonicysta? mutabilireta (DK-2) (Member XVII–lower part of Submember XVIIIb, interval of samples 3169/20-3169/35). Extremely poor assemblage (Fig. 9). The most complete quantitative characterization was obtained in sample 3169/20, which contains *Eatonicysta? mutabilireta* Pearce, 2010, Lanternosphaeridium lanosum Morgenroth, 1966, Isabelidinium cf. magnum (Davey, 1970) Stover et Evitt, 1978, Membranilarnacia polycladiata Cookson et Eisenack in Eisenack, 1963, Batiacasphaera cf. euteiches (Davey, 1969) Davey, 1979, Heterosphaeridium verdieri Yun Hyesu, 1981, Circulodinium distinctum (Deflandre et Cookson, 1955) Jansonius, 1986. In the higher part of the section (locality 3169) palynomorphs are represented by a few specimens. Using the presence of Eatonicysta? mutabilireta Pearce, 2010, first described from the undivided Burnham-Flamborough Chalk in the Trunch Borehole section (southeast England (Pearce, 2010)) and having a narrow stratigraphic range within the Gonioteuthis quadrata Zone (Fig. 10), interval DK-2 is compared with the middle-upper parts of the lower Campanian.

Assemblage with Odontochitina porifera-Nelsoniella aceras (DK-3) (Submember XVIIIb-lower part of Submember XIXa, interval of samples 3169/40–3169/60). The composition of the dinocyst assemblage from bottom to top along the section is enriched, mainly due to taxa of wide stratigraphic distribution, as well as Turnhosphaera hypoflata (Yun Hyesu, 1981) Slimani, 1994, Membranigonyaulax wilsonii Slimani, 1994, Hystrichosphaeropsis obscura Habib, 1972; etc. (Fig. 9). In the interval of the section characterized by DK-3, both the number of taxa and abundance of various Spin*iferites* species increase from bottom to top, the latter eventually becoming dominant (Fig. 9). This is the only level with Isabelidinium cretaceum (Cookson, 1956) Lentin et Williams, 1977a, Odontochitina porifera Cookson, 1956, and Nelsoniella aceras Cookson et Eisenack, 1960; their widespread distribution is characteristic of the Campanian and Maastrichtian sections of the Southern Hemisphere.

Presence in DK-3 of *Turnhosphaera hypoflata* (Yun Hyesu, 1981) Slimani, 1994, *Palaeohystrichophora infusorioides* Deflandre, 1935, *Rhynchodiniopsis salio-rum* Louwye, 1997, *Acanthaulax wilsonii* Yun Hyesu, 1981, *Membranigonyaulax wilsonii* Slimani, 1994, the co-occurrence of which is indicated for the dinocyst "A" Zone, established at the level of the Gonioteuthis quadrata Zone of Belgium (Slimani, 2001), suggests the early Campanian age of the host beds (Fig. 10).

In sections of the Helvetic and Ultra-Helvetic nappes of Germany, Odontochitina porifera Cookson, 1956 and Apteodinium deflandrei (Clarke et Verdier, 1967) Lucas-Clark, 1987 were recorded within the "4 Areoligera coronata" Zone, which embraces most of the Campanian, from the middle of the planktonic foraminiferal Globotruncanita elevata Zone to the Radotruncana calcarata Zone (Kirsch, 1991). In the Upper Cretaceous sections of England, the first appearance of single specimens of Odontochitina porifera Cookson, 1956 was identified in the mid-Coniacian, and a constant presence is recorded from the Uintacrinus socialis Zone of the upper Santonian (Pearce et al., 2020). In Austrian and Hungarian sections, this taxon is recorded at the level of the dinocyst Apteodinium deflandrei Subzone of the Odontochitina operculata Zone and nannoplankton CC18-CC19 zones (lower half) (Siegl-Farkas and Wagreich, 1996; Siegl-Farkas, 1997). The appearance of Odontochitina porifera Cookson, 1956 in the Polar Cis-Urals was established in the lower Campanian at the base of the Beds with Chatangiella niiga (Lebedeva, 2005, 2006).

According to the distribution of the index species, this part of the section can be compared with the Beds with the dinocyst *Odontochitina porifera* established in the Pudovkin Formation of the Lower Volga region within the BF Cibicidoides temirensis/Bolivinoides decoratus Zone (LC13) and the lower Campanian radiolarian Beds with *Prunobrachium crassum*—*Archaeospongoprunum salumi* (Alexandrova et al., 2012a).

The composition of dinocysts does not allow accurate dating of the host rocks in this part of the section. In terms of its position and based on foraminiferal assemblages and magnetostratigraphic data, the DK-3 interval corresponds to the lower-upper Campanian boundary beds (Fig. 10).

**Plate VI.** Calcareous microproblematics. (1–5) *Tubellus hunzikeri* (Odin, 2008), Sample 3169/24: (1) specimen 2022-4/14, a longitudinal structure is observed on the funnel stalk; (2) specimen 2022-4/13, the funnel is covered with mesh fabric; longitudinal rows of pores are visible along the perimeter of the funnel towards the center; (3) specimen 2022-4/19, at the junction of the bellshaped cone of the funnel and the oral opening; (4) specimen 2022-4/9, the oral surface is round in shape, slightly concave, the cone-shaped wall of the funnel has a striated structure, which continues on the stalk; (5) specimen 2022-4/31, in the center of the oral opening, the mesh of the inner layer is clearly visible, constituting for a third of the diameter of the funnel; (6) *Cimicellus nudatus* Odin, specimen 2022-4/44, Sample 3169/20; note the concavity of the sides of the funnel cone; (7) *Corniculum sinuosum* Odin, 2008, Sample 3169/20, specimen 2022-4/42; in the center of the funnel there is a round hole that is a quarter of its diameter; (8–10) *Aturella angulata* Odin: (8, 9) specimen 2022-4/43, Sample 3169/20; (10) specimen 2022-4/10, Sample 3169/24: (8, 9) upper view, (10) lateral view; (11, 12) *Azymella cannabinata* Odin, Sample 3169/20; (11) specimen 2022-4/38, (12) specimen 2022-4/57; note structure of lines intersecting in two perpendicular directions, like a canvas; (13) *Numismella tarbellica* Odin, specimen 2022-4/24, Sample 3169/24, radial structure is clearly visible. Scale bar: left–100 µm (1, 7–10), right–100 µm (other images).

![](_page_24_Figure_1.jpeg)

#### BARABOSHKIN et al.

![](_page_25_Figure_1.jpeg)

![](_page_25_Figure_2.jpeg)

Assemblage with *Exochosphaeridium? masureae*– *Tarsisphaeridium geminiporatum* (DK-4) (middle part of Submember XIXa, interval of samples 3169/65– 3169/85). The dinocyst association is very diverse, with more than 80 taxa identified (Fig. 9). The composition of dinocysts at this level is significantly enriched by new taxa in addition to aforementioned ones. The following taxa are recorded beginning from the base of this interval (sample 3169/65): *Exochosphaeridium?masureae* Slimani, 1996, *Exochosphaeridium* cf. *muelleri* Yun Hyesu, 1981, *Gillinia hymenophora* Cookson et Eisenack, 1960a, *Trithyrodinium suspectum* (Manum et Cookson, 1964) Davey, 1969, cf. *Renidinium vitilare* (Cookson, 1965) Stover et Evitt,

STRATIGRAPHY AND GEOLOGICAL CORRELATION Vol. 32 No. 2 2024

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116

1978, Pervosphaeridium intervelum Kirsch, 1991, cf. Dapsilidinium ambiguum (Deflandre, 1937) Wheeler et Sarjeant, 1990, Xenascus ceratioides (Deflandre, 1937) Lentin et Williams, 1973, Cometodinium whitei (Deflandre et Courteville, 1939) Stover et Evitt, 1978, Trigonopyxidia ginella (Cookson et Eisenack, 1960) Downie et Sarjeant, 1965 and prasinophyte Tarsisphaeridium geminiporatum Riegel, 1975, in the middle and upper parts – Fromea chytra (Drugg, 1967) Stover et Evitt, 1978, various species Dinogvmnium, Cleistosphaeridium aciculare Davey, 1969; etc. The assemblage of dinocysts is characterized by the predominance of *Spiniferites* spp. (Cookson, 1965) Stover et Evitt, 1978, Trithyrodinium suspectum (Manum et Cookson, 1964) Davey, 1969, Cometodinium whitei (Deflandre et Courteville, 1939) Stover et Evitt, 1978, Xenascus ceratioides (Deflandre, 1937) Lentin et Williams, 1973 and prasinophytes Tarsisphaeridium geminiporatum Riegel, 1975, as well as abundant and diverse representatives of the genus *Dinogymnium*.

The dinocyst DK-4 Assemblage based on the presence of *Exochosphaeridium? masureae* Slimani, 1996, *Acantaulax wilsonii* Yun Hyesu, 1981, *Rhynchodiniopsis saliorum* Louwye, 1997, *Whitecliffia spinosa* (Clarke et Verdier, 1967) Pearce, 2010, *Fromea chytra* (Drugg, 1967) Stover et Evitt, 1978 confidently corresponds to Subzone "a" of the Exochosphaeridium? masureae Zone of Belgium, established in the lower part of the Belemnitella mucronata Zone (Slimani, 2001; Slimani et al., 2011), which indicates the late Campanian (in case of the Campanian bipartite subdivision) age of the host beds (Fig. 10).

Frequent occurrence of the prasinophytes *Tarsi-sphaeridium geminiporatum* Riegel, 1975 was recorded in Hungarian and Austrian sections in the Tarsi-sphaeridium geminiporatum Subzone of the dinocyst Odontochitina operculata Zone at the level of nanno-plankton zones CC19 (C. ovalis, second half)–CC20 (C. aculeus) (Siegl-Farkas and Wagreich, 1996; Siegl-Farkas, 1997). The above allows dating the interval with the DK-4 dinocyst assemblage as the first half of the late Campanian.

The high diversity of dinocysts in DK-4, as well as the frequent occurrence of the prasinophyte *Tarsisphaeridium geminiporatum* Riegel, 1975, classified in the family Tasmanitaceae (Tappan, 1980), indicate warm near-tropical depositional environment. This part of the section probably corresponds to the socalled "Mid-Campanian event"—a positive  $\delta$ 13C isotopic excursion established at the base of the Belemnitella mucronata Zone (Jenkyns et al., 1994; Jarvis et al., 2002, 2006; Voigt et al., 2010) and associated with a large "mucronata- transgression".

Assemblage with *Xenascus wetzelii*—cf. *Biconidinium reductum* (DK-5) (upper part of Submember XIXa, sample interval 3169/90–3169/95). DK-5 shows poor preservation of dinocysts and many damaged specimens. Most of the taxa encountered lower in the section continue to this level. The following taxa appear for the first time: Xenascus wetzelii Slimani, 1996, Neosphaerodictyon filosum Slimani, 2003, cf. Biconidinium reductum (May, 1980) Kirsch, 1991, Chatangiella? robusta (Benson, 1976) Stover et Evitt, 1978, Hystrichosphaeridium proprium Slimani, 2003, Dinogymnium nelsonense (Cookson, 1956) Evitt et al., 1967, Dinogymnium microgranulosum Clarke et Verdier, 1967. Dinogymnium longicorne (Vozzhennikova, 1967) Harland, 1973, Coronifera oceanica subsp. hebospina Yun Hyesu, 1981, Tanyosphaeridium variecalamum Davey et Williams, 1966, Hystrichostrogylon sp., Ithnacvsta elongata Slimani, 1994, Montanarocvsta aemiliana Corradini, 1973, Exochosphaeridium striolatum (Deflandre, 1937) Davey, 1969, Fromea fragilis (Cookson et Eisenack, 1962) Stover et Evitt, 1978; etc. (Fig. 9).

The assemblage is characterized by the dominance of Spiniferites spp. and frequent occurrence of *Fromea chytra* (Drugg, 1967) Stover et Evitt, 1978, *Trithyrodinium suspectum* (Manum et Cookson, 1964) Davey, 1969, *Xenascus wetzelii* Slimani, 1996, *Palaeohystrichophora infusorioides* Deflandre, 1935, *Gillinia hymenophora* Cookson et Eisenack, 1960, cf. *Biconidinium reductum* (May, 1980) Kirsch, 1991, *Tarsisphaeridium geminiporatum* Riegel, 1975.

The first appearance of *Xenascus wetzelii* Slimani, 1996, cf. *Biconidinium reductum* (May, 1980) Kirsch, 1991 and their co-distribution with *Exochosphaeridium? masureae* Slimani, 1996, *Rhynchodiniopsis saliorum* Louwye, 1997, *Acanthaulax wilsonii* Yun Hyesu, 1981, *Whitecliffia spinosa* (Clarke et Verdier, 1967) Pearce, 2010 allow the correlation of this part of the section with Subzone "b" of the *Exochosphaeridium? masureae* Zone of Belgium, established in the upper part of the Belemnitella mucronata Zone (Slimani, 2001; Slimani et al., 2011), which indicates its Late Campanian age (Fig. 10). However, no taxa characteristic of the second half of the late Campanian were found.

As a result of the analysis of data on dinocysts, it was shown that in the Kudrino-1 section there is a reliably present level of the middle part of the lower Campanian—the base of the upper Campanian in the case of bipartite subdivision, and the boundary of the lower and upper substages passes within the interval with the DK-3 dinocyst assemblage, between samples 3169/50 and 3169/55.

### MAGNETOSTRATIGRAPHY

#### Petromagnetic and Magneto-Mineralogical Studies

**Methods.** In the Kudrino-1 section, oriented samples were selected from 102 levels for paleo- and petromagnetic studies using an entrenching tool. For laboratory measurements, 3-4 cubic samples measuring  $2 \times 2 \times 2$  cm were cut from each sample. Mass petromagnetic studies included measurements of the following parameters: K – magnetic susceptibility and anisotropy of magnetic susceptibility (AMS);  $K_t$  (thermo-

Vol. 32 No. 2 2024

kappa) – magnetic susceptibility after heating rocks at a temperature of 500°C for an hour (the increase dK = $K_t - K$  in this case reflects the content of finely dispersed pyrite in the sample, due to the phase transition of non-magnetic FeS<sub>2</sub> to highly magnetic Fe<sub>3</sub>O<sub>4</sub> at temperatures above  $400^{\circ}$ C); J<sub>n</sub>-natural remanent magnetization;  $J_{rs}$ —saturation remanent magnetization (the maximum possible remanent magnetization in the sample, created by an artificial magnetic field);  $\mathbf{B}_{cr}$ —the field corresponding to the residual coercive force that must be applied to completely destroy the  $J_{rs}$ of the sample. In addition to the characteristics established experimentally, the following parameters were calculated: factor Q (Koenigsberger ratio), equal to the ratio of  $J_n$  to inductive magnetization; magnetic hardness parameter  $S = -J_{r(-300)}/J_{rs}$  (where  $J_{r(-300)}$  is the remanent magnetization after exposure to a field of 300 mT, opposite to the direction of the saturation field) and the ratio  $\mathbf{K}/\mathbf{J}_{rs}$ . Factor  $Q \ge 1$  indicates a high-order harmonics of the magnetic moments of particles. Values of parameter S close to zero indicate the dominance of the hard magnetic phase in the sample, while values close to 1 indicate the predominance of soft magnetic minerals. The  $K/J_{rs}$  ratio is proportional to the mean size of ferromagnetic grains, provided that the type of mineral carrier  $J_n$  is constant.

K measurements were conducted using a MFK1-FB Kappabridge,  $J_n$ —on a JR-6 spin magnetometer. The hysteresis characteristics ( $J_{rs}$ ,  $B_{cr}$ ) were obtained using a controlled electromagnet with a maximum field intensity of 700 mT (therefore, in this work, the remanent magnetization after exposure to a field with an intensity of 700 mT, which is obviously sufficient to saturate soft magnetic samples, is conventionally taken as  $J_{rs}$ ). The *dK* value was measured after heating the samples in a SNOL-6/11-V muffle furnace. AMS data analysis was carried out using the Anisoft 5.1.03 software package (agico.com).

Selected samples were subjected to thermomagnetic analysis (TMA) on a TAF-2 thermal fraction analyzer ("magnetic balance") and studied on a J\_meter coercivity spectrometer at Kazan Federal University. Paleomagnetic studies followed the standard method (Molostovsky and Khramov, 1997), which consisted in measuring  $J_n$  of oriented samples on a JR-6 spin magnetometer after demagmetization with an alternating field ( $\dot{H}$ ) or temperature ( $T^{\circ}$ ). Possible phase transformations of minerals during heating were controlled by measuring K of the samples after each thermal demagnetization. The H-demagnetizing was performed using an LDA-3AF demagnetizer, and for thermal demagnetization, an Aparin thermal oven was used. Paleomagnetic studies of samples from 33 different levels were duplicated on a 2G-Enterprices cryogenic magnetometer (SQUID) at the Institute of Physics of the Earth of the Russian Academy of Sciences (Moscow). The Remasoft 3.0 software package (Chadima and Hrouda, 2006) was used for component analysis.

Magnetic mineralogy and petromagnetism. Soft magnetic minerals are carriers of magnetization in the sediments under study. Values of the parameter *S* close to one, fields corresponding to values of the residual coercive force of 35–55 mT, and saturation fields ( $\mathbf{B}_{s}$ ) < 300 mT (Figs. 11, 12a) are characteristic of finely dispersed magnetite and/or titanomagnetites, similar in composition to Fe<sub>3</sub>O<sub>4</sub>. A single increase in  $\mathbf{B}_{cr}$  to 114 mT (Fig. 11) is most likely associated with magnetically hard iron hydroxides—products of the oxidation of magnetite (titanium magnetites) and/or pyrite.

It was not possible to diagnose magnetite (like other magnetic phases) from thermomagnetic curves due to the extremely low concentration of ferromagnets. However, in the neighboring Kudrino-2 section, in which the lower Submember XVIa is exposed, subtle inflections in the area of the Curie temperature of  $Fe_3O_4 - 578^{\circ}C$  were recorded on some TMA curves, as well as thermomagnetic effects characteristic of titanomagnetites from volcanic ash (Guzhikov et al., 2021b). The coercitometric characteristics of the samples on the Day plot (Fig. 12b) are located near the section of the theoretical curve corresponding to pseudo-single domain magnetite (Dunlop, 2002). The magnetic texture of the studied sediments corresponds to the primary texture of sediments with allotigenic ferromagnets (short axes of magnetic ellipsoids (K3) are grouped in the center, and long and medium axes (K1 and K2, respectively) are evenly distributed along the margin of the stereo projection; Fig. 12c-I), which is favorable a prerequisite for the preservation of primary magnetization. The magnetic anisotropy index P, with rare exceptions, varies from 1 to 1.4, indicating a close to isometric shape of ferromagnetic particles

Plate VII. Dinocysts and acritarchs of the Kudrino-1 section. All figures are at one magnification. (1, 2) *Eatonicysta mutabilireta* Pearce, 2010, (1)Sample 3169/20, (2) Sample 3169/35; (3, 4) *Odontochitina porifera* Cookson, 1956, Sample 3169/45; (5) *Rhyn-chodiniopsis saliorum* Louwye, 1997, Sample 3169/50; (6) *Nelsoniella aceras* Cookson et Eisenack, 1960a, Sample 3169/40; (7) *Tarsisphaeridium geminiporatum* Riegel, 1975, Sample 3169/65; (8) *Exochosphaeridium ?masureae* Slimani, 1996, Sample 3169/65; (9) cf. *Biconidinium reductum* (May, 1980) Kirsch, 1991, Sample 3169/05; (10) *Acanthaulax wilsonii* Yun Hyesu, 1981, Sample 3169/65; (11) *Isabelidinium bakeri* (Deflandre et Cookson, 1955) Lentin et Williams, 1977a, Sample 3169/85; (12) *Dinogymnium muticum* (Vozzhennikova, 1967) Lentin et Williams, 1973, Sample 3169/85; (13) *Membranigonyaulax wilsonii* Slimani, 1994, Sample 3169/65; (14) *Membranilarnacia polycladiata* Cookson et Eisenack in Eisenack, 1963a, Sample 3169/50; (15) *Xenascus ceratioides* (Deflandre, 1937b) Lentin et Williams, 1973, Sample 3169/65; (16) *Raetiaedinium truncigerum* (Deflandre, 1937) Kirsch, 1991, Sample 3169/65; (17) *Xenascus wetzelii* Slimani, 1996, Sample 3169/90; (18) *Pervosphaeridium intervelum* Kirsch, 1991, Sample 3169/70; (19) *Whitecliffia spinosa* (Clarke et Verdier, 1967) Pearce, 2010, Sample 3169/95.

![](_page_30_Figure_1.jpeg)

![](_page_31_Figure_1.jpeg)

![](_page_32_Figure_1.jpeg)

**Fig. 11.** Magnetostratigraphic section Kudrino-1. The petromagnetic plots show shaded intervals, in which the parameter values exceed the median parameter values throughout the section. Shaded areas in the lower part of the paleomagnetic log "Magnetozone (chron)" indicate areas to which reverse polarity determinations are interpolated or extrapolated. Legend: I—normal polarity; III—reverse polarity; III—lack of polarity data; 1, 2—**ChRM**; 3, 4, 5–**J**<sub>st</sub>; 6, 7—large circles based on the results of H-demagnetization on SQUID (1, 3, 6), JR-6 (2, 4, 6) and T°-demagnetization on JR-6 (5); 8—level of the boundary of petromagnetic complexes (PC), combined with the lithological boundary; 9—alternative options for justifying the PC boundary, 10—boundaries of petromagnetic intervals (PI).

STRATIGRAPHY AND GEOLOGICAL CORRELATION Vol. 32 No. 2 2024

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**Fig. 12.** Results of magneto-mineralogical studies. (a) Magnetic saturation and destruction curves; (b) Day plot (SD, PSD and MD—areas of single-domain, pseudo-single-domain and multi-domain particles, respectively); (c) data on the anisotropy of magnetic susceptibility: stereograms of projections of the long (K1), medium (K2) and short (K3) axes of the AMF in the paleo-geographic coordinate system (isolines reflect the concentration of K3) and P–T plots (P is the anisotropy index, positive and negative T values indicate flattened and elongated shapes of ferromagnetic particles, respectively). I–AMB data for the entire section, II–AMB data for the base of the section (below the level of sample 3169/53), III–AMB data for the top of the section (above the level of sample 3169/52). *n*–number of samples. Legend: 1, 2, 3–middle directions with confidence ovals *K1*, *K2* and *K3*, respectively.

(Fig. 12c-I). At first glance, it may seem that significant deviations of K3 from the vertical and increased **P** are characteristic only of the basal part of the section, while the top beds are characterized by an almost ideal primary magnetic texture and an almost isometric

shape of magnetic particles ( $\mathbf{P} \le 1.1$ ). However, a comparison of the AMS data with the value of magnetic susceptibility leaves no doubt that the spread in K3 and the increase in  $\mathbf{P}$  are mainly due to measurement errors, because they are recorded only in the weakest

magnetic samples (Fig. 12c-II) and are absent in the sample with a relatively high magnetic susceptibility (Fig. 12c-III). The studied rocks are very weakly magnetic: magnetic susceptibility varies from (-0.1) to 2  $\times$  $10^{-5}$  SI units (more than 75% of samples are characterized by  $K < 1 \times 10^{-5}$  SI units), and natural remanent magnetization varies from 0.01 to  $0.3 \times 10^{-3}$  A/m (over 80% of samples have  $J_n < 0.05 \times 10^{-3}$  A/m) (Fig. 11). Despite this, the Kudrino-1 section is differentiated in petromagnetic terms: the top beds of the section (samples 3169/41–3169/102) differ from the underlying deposits in increased values of K,  $K/J_{rs}$  and (not so clearly) dK relative to the median (Fig. 11). The beginning of a stable excess of the median values of K and  $K/J_{rs}$  is preceded by anomalous peaks Q and  $J_n$ (sample 3169/40), which most clearly define the level of the boundary between the lower and upper petromagnetic complexes (PC-1 and PC-2, respectively). The location of the boundary between PC-1 and PC-2 at the base of Member XIX (Fig. 11) is natural, because both the lithological features and the magnetic properties of the rocks are determined by the changes in the depositional settings. Therefore, the level of Sample 3169/40 (more precisely, between samples 3169/40 and 3169/41) we place at the base of Submember XIXa, corresponding to the upper Campanian according to (Alekseev, 1989). Low, even by the standards of sedimentary rocks, Q values (mostly ca. 0.01-0.1) are typical of the detrital nature of magnetization, which is consistent with the assumption of a predominantly allotigenic origin of ferromagnets based on AMS materials. In this case, the increased magnetic susceptibility of the upper sections can be associated with a slowdown in the rate of supply of carbonate micrite, as a result of which allotigenic components in PC-2 are diluted to a lesser extent than in PC-1, and variations in K along the section should be considered as an inverse reflection of the sedimentation rate (Guzhikov and Surinsky, 2017). The lower boundaries of Submember XVId2, Member XVII, Sunmembers XVIIIa and XVIIIb as a whole are not directly reflected in petromagnetism, but petromagnetic rhythmicity in this part of the section is well manifested in the Q and  $J_n$  plots (Fig. 11). A feature of PC-1 is the presence of individual levels with maximum Qvalues (several units), combined, as a rule, with increased  $J_n$  values (> 0.1 × 10<sup>-3</sup> A/m) (Fig. 11). These magnetic anomalies are not accompanied by significant changes in other magnetic properties, which makes it possible to exclude their connection with an increase in concentrations or the appearance of new types of ferromagnetic minerals. The remaining options for interpreting the nature of Q bursts allow either a sharp increase in the geomagnetic field strength during rock formation, or the chemical genesis of magnetization. If the latter version is correct, the carrier of chemical magnetization may be authigenic magnetite, possibly of biogenic origin, produced during a slowdown in sedimentation rate or short-term gaps in sedimentation. Under such circumstances, Q anomalies record the natural boundaries of fractional lithological units (Fig. 11), and the location of three of the five petromagnetic boundaries identified within PC-1 to the base of Submember XVId2, Member XVII, submembers XVIIIa and XVIIIb (Fig. 11) is not random. The tops of the section (within PC-2) can also be additionally subdivided according to the features of the vertical distribution of petromagnetic parameters. Variations in the  $J_{rs}$  graph form three rockmagnetic intervals (PI-2.1, PI-2.2 and PI-2.3), the middle of which is distinguished by increased values of this parameter (Fig. 11). The base of PI-2.2 is marked by increasing  $J_{rs}$ . The base of PI-2.3, recorded by a decrease in the parameter, is less expressive, but this interval is additionally individualized by a noticeable decrease in  $\mathbf{B}_{cr}$  and an increase in S. Probably, the decrease in magnetic hardness is associated with less intense oxidation of magnetite grains.

**Paleomagnetism.** The paleomagnetic quality of the studied rocks cannot be considered good, but a comprehensive analysis of the data obtained makes it possible to give a magnetopolar characteristic of the section, suitable for use for magnetostratigraphy. H demagnetization, which involved the JR-6 spin magnetometer and the LDA-3AF setup, were carried out up to 20 mT (in rare cases up to 30-40 mT), in steps of 2 mT. Further demagnetization was impossible, because when exposed to higher fields, the magnitude of the magnetization became comparable to the measuring error of the device, and the directions of J<sub>n</sub> changed chaotically.  $\tilde{H}$ -demagnetization using a cryogenic magnetimeter made it possible to trace changes in the magnetization vector up to 50 mT (rarely up to 60 mT), in

netization vector up to 50 mT (rarely up to 60 mT), in steps of 1-4 mT in the range up to 20 mT, and in steps of 4-5 mT in the range above 20 mT. The results of demagnetization by an alternating field, obtained on different instruments in independent laboratories, showed good convergence (Fig. 13a), which allows one to trust the results of measurements on a spin magnetometer, despite the limited upper range of the demagnetization field.

Small values of  $J_n$  (often <0.000015 × 10<sup>-3</sup> A/m even after the weakest effects of alternating field or temperature) are the reason for the low quality of Zijderveld diagrams constructed from the results of measurements on both JR-6 and SQUID (Figs. 13b, 13c). Nevertheless, in most diagrams it is possible to identify areas, when approximated by straight line segments, the maximum angle of deviation (MAD) is less than 15° (otherwise the  $J_n$  components were not identified). In samples from 26 levels, characteristic components of magnetization (**ChRM**) were identified, in the calculation of which the coordinate center was taken into account as the end point (Figs. 13b, 13c). If the straight line approximating the diagram interval significantly deviated from the direction towards the origin of coordinates, then additional points were not included in the calculations, and the selected magnetization components were conventionally referred to as "stable" ( $J_{st}$ ). It was not possible to isolate any  $J_n$  components in samples from 22 levels. Thermal demagnetization performed in the range from 100 to 400°C, in increments of 50°C, were ineffective (with the exception of 3 levels, at which it was still possible to isolate  $J_{st}$ ). In samples with 13 levels in the lower part of the section, the  $J_n$  projections shift along great circle (GC) arcs during demagnetization (Fig. 13d).

The tops of the section (samples 3169/53-3169/102) are characterized by magnetization components grouped in the northern directions of the lower hemisphere (Figs. 11, 13b, 14a). Such directions are typical for the direct polarity (N, n) of the geomagnetic field. The base of the section (samples 3169/1-3169/52) are marked by a chaotic distribution of  $J_n$ components on the sphere and the presence of GC (Figs. 11, 13c, 14b). Some components are projected onto the southern bearings of the upper hemisphere, which is typical for the reverse polarity (R, r) of the field, others correspond to direct polarity. A significant part of  $J_{st}$  (less commonly **ChRM**) has southern declinations (D) with positive (often flat) inclinations (I) or northern declinations with negative inclinations. In the practice of magnetostratigraphic studies, such anomalous directions are often encountered. As a rule, they represent stabilized sums of two antiparallel components-the primary one, corresponding to the reverse polarity, and the secondary one, associated with the modern field. Different degrees of "contamination" of the total magnetization by the viscous component lead to a very large scatter in  $J_{st}$  in the case of the opposite sign of ancient magnetization and have less of an effect on paleomagnetic statistics for initially normally magnetized samples due to the fact that the directions of the modern and Late Cretaceous normal fields are similar. The presence of multidirectional magnetization components is also the reason for the displacement of paleomagnetic vectors along great circle arcs (Guzhikov et al., 2010, 2021a; Karpuk et al., 2018; etc.). Therefore, in the paleomagnetic column at levels where GC or anomalous  $J_n$  components with negative and slightly positive ( $<20^\circ$ ) inclinations are recorded, a sign of reverse polarity is shown (Fig. 11). Regarding the structure of the paleomagnetic log, it should be noted that levels with direct polarity are found everywhere, while those with reverse polarity are only in the lower half of the section, no higher than the interval between samples. 3169/52 and 3169/53 (Fig. 11). Of the 12 n-intervals recorded at the base of

the section, 10 are substantiated by samples from one, and 2-from two levels, while to isolate the magnetic zone it is necessary to document the same polarity sign at at least three adjacent levels (Khramov and Sholpo, 1967). Meanwhile, in a number of areas, r-intervals are grouped in the section into three (samples 3169/12-3169/15, samples 3169/30-3169/33), four (samples 3169/25-3169/29, samples 3169/37-3169/40), even at seven (sample 3169/17 - 3169/23) levels in a row (Figs. 11, 14c). Since, in accordance with formal requirements (Khramov and Sholpo, 1967), single nintervals should not be taken into account when identifying magnetostratigraphic units, the base of the section (samples 3169/1-3169/52) remains characterized only by R-zones, which are combined into one large zone of reverse polarity  $(\mathbf{R}_1)$ . The identification of a zone of direct polarity  $(N_1)$  at the top of the section (samples 3169/53-3169/102) does not require additional argumentation (Fig. 11).

It is impossible to apply standard field tests to the obtained materials, because the data used to substantiate the  $\mathbf{R}_1$  zone (Figs. 13b, 14c) are unsuitable for calculating paleomagnetic statistics, and there are no prerequisites for testing folds and conglomerates. But the primacy of  $\mathbf{J}_n$  can be judged by a number of indirect signs, the totality of which indicates that the sequence of magnetic zones recorded by us reflects the regime of the Campanian geomagnetic field:

(1) Intervals of the same polarity sign, determined by the **ChRM** directions, are naturally grouped along the section, forming two large magnetozones  $- R_1$  and  $N_1$  (Fig. 11).

(2) The independence of the polarity sign from the material composition and physical properties of the rocks is a sign of the ancient nature of  $J_n$ , while the association of one or another polarity with a certain type of sediment suggests a possible magnetization reversal. There is no obvious connection between the identified magnetic zones and lithological and petromagnetic units, but the confinement of sections of the section with a more reliably substantiated reverse polarity to the weakly magnetic PC-1 and the coincidence of the top of the  $\mathbf{R}_1$  Zone with the base of the PI-2.2 magnetic rhythm at first glance, seem suspicious. However, the presence of the R-zone in the Kudrino-2 section (comparable in terms of the quality of paleomagnetic determinations with the  $\mathbf{R}_{\mathbf{1}}$  Zone in Kudrino-1) in the "strongly magnetic" (K =  $1-2 \times 10^{-5}$  SI units and over) lower Submember XVIa (Guzhikov and al., 2021a) refutes the assumption of a correlation of the opposite sign of polarity with minimum values of mag-

**Fig. 13.** Typical results of component analysis (polar stereo projections, Zijderveld diagrams, demagnetization plots). (a) Comparison of the results of H-demagnetization of duplicate samples on JR-6 and SQUID; (b–d) results for samples in which **ChRM** corresponding to direct polarity (b), reverse polarity (c) and large circles (d) are identified. All data are presented in the stratigraphic coordinate system. Legend: 1–4–projections of  $J_n$  onto the lower (1) and upper (2) hemispheres, onto the horizontal (3) and vertical (4) planes; 5, 6–segments approximating **ChRM** (5) and the "low-coercivity" component  $J_n$  (6).

![](_page_36_Figure_1.jpeg)

STRATIGRAPHY AND GEOLOGICAL CORRELATION Vol. 32 No. 2 2024

![](_page_37_Figure_1.jpeg)

Fig. 13. (Contd.)

![](_page_38_Figure_1.jpeg)

Fig. 14. Polar stereo projections of the  $J_n$  components (in the stratigraphic coordinate system). (a) At the top of the section (above the level of sample 3169/52), (b) at the base of the section (below the level of sample 3169/53), (c) in the interval between samples. 3169/17–23. *n*–number of samples in the sample, D, I–declination and inclination of the average paleomagnetic vector, respectively, *k*–interbed grouping,  $\alpha_{95}$ – confidence radius. Legend: 1–4–projections of  $J_n$  components with confidence circles (the radius of which is MAD) onto the lower (1, 2) and upper (3, 4) hemispheres (components determined from measurement data on JR-6 (1, 3) and SQUID (2, 4), confidence circles shown for ChRM only); 5, 6–projections of average paleomagnetic directions with circles of confidence ( $\alpha_{95}$ ) for them onto the lower (5) and upper (6) hemispheres. For other symbols, see Fig. 13.

netic susceptibility. Abrupt changes in petromagnetic parameters, as a rule, correspond to breaks in sedimentation (Guzhikov, 2013), and a sharp increase in  $J_{rs}$  values at the base of PI-2.2 most likely records a short-term cessation or slowdown of sedimentation. The coincidence of paleomagnetic and petromagnetic boundaries at the break level is not uncommon.

(3) The average paleomagnetic direction determined from the N-zone (Fig. 14a) statistically coincides with the average direction in the upper Campanian–Maastrichtian deposits of the Beshkosh section (approximately 4.5 km N–NW from the Kudrino-1 section) (Baraboshkin et al., 2020), but it differs significantly in the direction of the modern field in the stratigraphic coordinate system. In the first case, the angle between the vectors (4.7°) is less than the error ( $\pm 6.7^{\circ}$ ) determined according to (Debiche and Watson, 1995); in the second, on the contrary, it is larger: 9.8°  $\pm$  9.5°. (During statistical testing, the maximum amplitude of secular variation was taken as  $\alpha$ 95 for the modern field—10° (Bakhmutov, 2006).)

(4) The obtained paleomagnetic data correspond to the criterion of external convergence, that is, they are consistent with known ideas about the magnetopolar structure of the Campanian (Gradstein et al., 2020). Taking into account the obtained paleontological data on the Campanian (Early and Late Campanian) age of sediments in the identified magnetic zones  $\mathbf{R}_1$  and  $\mathbf{N}_1$ , analogues of chrons 33r and 33n, respectively, are easily identified (Fig. 11).

Evidently, in the Kudrino-1 section, the top part of chron 33r was discovered, the basal horizons of which

were previously recorded in the neighboring Kudrino-2 section and, probably, in Aksu-Dere (Guzhikov et al., 2021a, 2021b). Due to the consistent occurrence of the beds (dipping west–northwest at angles from  $9^{\circ}$  to  $19^{\circ}$ ), it is possible to estimate the true thickness of the analogue of chron 33r in the area of the village of Kudrino. It is approximately 120 m (in the calculation, a horizontal distance of 500 m was used, taken between the base 33r in the Kudrino-2 section (Guzhikov et al., 2021a, 2021b) and the estimated top of this chron in the Kudrino-1 section, the average dip azimuth is  $310^{\circ}$ and dip angle is  $14^{\circ}$ ). The mean sedimentation rate is defined as the ratio of the thickness of rocks to the duration of the time interval during which they were deposited. Taking into account data on the duration of 33r (~3 Ma; Gradstein et al., 2020), the average rate of deposition in the Kudrino-1 and Kudrino-2 sections during the reverse polarity chron was approximately 4 cm/ka.

## ISOTOPIC-GEOCHEMICAL ANALYSIS

**Methods.** The isotopic composition of carbon (C) and oxygen (O) in the samples was measured using a Delta V Advantage mass spectrometer with a Gas-Bench II attachment (Laboratory of Isotope Geochemistry and Geochronology, Geological Institute, Russian Academy of Sciences). The carbonates were decomposed in 100% orthophosphoric acid at a temperature of 50°C. The  $\delta^{13}$ C and  $\delta^{18}$ O values are given in ppm relative to the VPDB standard. During calibration, international standards IAEA C-O-1 were used. Every 10 samples, a verification test was used to con-

![](_page_39_Figure_2.jpeg)

**Fig. 15.** Isotopic data  $\delta^{13}C_{carb}$ , % VPDB and  $\delta^{18}O_{carb}$ , % VPDB for Campanian deposits of the Kudrino-1 section and characteristic intervals  $\delta^{13}C$  (Roman numerals). LCaE—Late Campanian Event.

trol the measurement accuracy. The error in determining  $\delta^{13}$ C and  $\delta^{18}$ O is  $\pm 0.1\%$  for  $\delta^{13}$ C and  $\pm 0.2\%$  for  $\delta^{18}$ O. The contents of Ca, Mg, Mn, Fe and Sr were not determined. The  $\delta^{18}$ O values in the studied limestones vary from -4.5 to -2.2‰ (Fig. 15). This is lower than in Mesozoic marine carbonates of the Tethyan paleobasins (from -2 to 0‰). As in the Kudrino-2 section (Guzhikov et al., 2021b), the values of  $\delta^{18}$ O and  $\delta^{13}$ C do not show any dependence on each other, which indicates the absence of epigenetic recrystallization with the participation of atmospheric waters (Pokrovsky et al., 2020). The  $\delta^{13}$ C values vary from 2.3 to 3.2‰ (Fig. 15) and are close to similar values in Mesozoic marine carbonates of the Tethyan and perithetic paleobasins (Thibault et al., 2016; Pearce et al., 2022; Jarvis et al., 2023). Based on  $\delta^{13}$ C values, several intervals can be distinguished, which are partially consistent with the identified lithological intervals. In interval I (Submember XVId1–XVId2),  $\delta^{13}$ C values vary from 2.0 to 2.9% (Fig. 15). In interval II (Member XVIIlower part of Submember XIXa, slightly above the top of chron C33r), the values are increased with a small scatter: from 2.4 to 2.9%. In interval III (Submember XIXa, samples 3169/54 - 3169/75), the  $\delta^{13}$ C values are maximum and vary from 2.8 to 3.2%. It is possible that this interval, which falls on the lower part of the upper Campanian, can be compared with the positive anomaly (or part of it) "BUCE"-Base Upper Campanian Event (Voigt et al., 2010, 2012; Wendler, 2013) or "MCaE"-Mid-Campanian Event (Pearce et al., 2022). The overlying interval IV (Submember XIXa, samples 3169/76-3169/90) is characterized by a steady decrease in  $\delta^{13}$ C values from 3.0 to 2.6%. Interval V (Submember XIXa, samples 3169/91-3169/101) begins with a single  $\delta^{13}$ C maximum of 3.1%, but higher values decrease again to 2.8–2.6%. Finally, the uppermost interval VI corresponds to a single minimum value of 2.3% (Submember XIXa, sample 3169/102). Perhaps this is an analogue of the "LCE" event-Late Campanian Event (Wendler, 2013), but to be confident in this conclusion, additional data that can be obtained from neighboring sections is needed. The correlation of the identified intervals with paleomagnetic and bioevents is discussed below.

# U-Pb ZIRCONS DATING

Methods. A sample of bentonite clavs (sample 1-2018) was placed in distilled water, and a suspension was prepared using ultrasonic dispersion, which made it possible to pre-separate high-density mineral fractions from the clays during the subsequent removal of clay suspension in water. The zircons were then isolated using standard techniques including heavy liquid separation and electromagnetic separation. Then 25 zircon grains were mounted in ultra-pure epoxy resin (a disk with a diameter of 25 mm and a thickness of about 4 mm) along with grains of the TEMORA zircon standard. The block was then polished down, so the interior of the zircon crystals was exposed. Observations under a microscope in transmitted and reflected light helped to identify clean areas of crystals, without cracks or microinclusions, suitable for ion microanalvsis. Before analysis, images of the crystals were obtained in cathodoluminescent radiation and backscattered electrons on a scanning electron microscope, which made it possible to identify the nature of zoning and the internal structure of zircon (Fig. 16). The U-Pb dating of zircons was conducted using a SHRIMP-II ion microprobe (secondary ion mass spectrometry with high spatial resolution) at the Geological Research Institute (VSEGEI) using standard

![](_page_40_Figure_1.jpeg)

**Fig. 16.** Concordia diagram showing U-Pb dating results of zircon from the Crimean bentonite ashes (a) and an image of crystals of dated zircons in cathodoluminescence radiation (b). The numbers correspond to the points in Table 1.

procedures (Williams, 1998). The measurement results were processed using the Isoplot software (Ludwig, 2012). Traditionally, for relatively young Cretaceous zircons, the age was calculated from the <sup>206</sup>Pb/<sup>238</sup>U ratio, since for such crystals, given the low amount of accumulated radiogenic <sup>207</sup>Pb and the large error in determining <sup>207</sup>Pb/<sup>206</sup>Pb, it is problematic to assess age discordance using two independent isotope systems. In this study, the <sup>206</sup>Pb/<sup>238</sup>U ages are corrected for <sup>207</sup>Pb (Williams, 1998), assuming that the slight zircon discordance is a consequence of simple mixing of common and radiogenic Pb. The reproducibility of SHRIMP analysis for the <sup>238</sup>U/<sup>206</sup>Pb isotope ratio in the standard is on the order of 1-2%(Black et al., 2004), which is equivalent to a dating error of 1-3 Ma or less for Phanerozoic zircons.

Results of U-Pb dating of zircons. Virtually all extracted zircon crystals measuring about 130-300 µm are well-faceted, transparent and elongated, with a thickness/length ratio from 1:3 to 1:8 (in most cases 1:5). This indicates their in situ origin, characteristic of volcanic ashes, probably of rhvolite or dacite composition. In cathodoluminescence radiation in crystals. oscillatory and sectorial zoning is observed, common for magmatic zircon (Fig. 16). The Th/U ratios in the 12 measured crystals vary from 0.9 to 1.6 (Table 1), which is also typical for zircon of igneous origin. The weighted average value of the concordant age for twelve zircon crystals was  $77 \pm 1$  Ma (MSWD = 0.08, p = 0.77, N = 12/12, Fig. 16), while in most crystals the age varies from 77 to 80 Ma, which corresponds to the early Campanian.

According to estimates (Gradstein et al., 2020), the C33r–C33n level of geomagnetic polarity change has an age of 79.9 Ma. The selected zircon samples come from the C33r reverse polarity interval, below the polarity reversal level. Taking into account the spread of the obtained absolute values, they are generally consistent with the indicated figure.

The dates differ somewhat from existing estimates of the age of biostratigraphic zones. According to (Walaszczyk, 1997), the top of the Inoceramus sarumensis—Cataceramus dariensis Zone approximately coincides with the top of the lower Campanian of the North American scale and can be dated as approximately 80.5 Ma (Walaszczyk et al., 2008), while in the Kudrino-1 section this level, although younger according to dating, is located below the level of finds of *Sphaeroceramus* cf. *sarumensis*.

According to dating of tuffs from sections in the United States, the lower-upper Campanian boundary of the European scale, corresponding to the base of the Baculites obtusus Zone (the base of the Middle Campanian of the North American scale), has an age of  $80.58 \pm 0.55$  Ma (Cobban et al., 2006, 2008). This level falls within the reverse polarity interval C33r (Leahy and Lerbekmo, 1995), like the sample from the Kudrino-1 section, and, as we see, is close to it in age.

Taking into account the insufficient precision of the SHRIMP instrument in terms of measurements of <sup>207</sup>Pb content and the associated difficulty of correctly assessing concordance, it can be accepted that the most likely age of the bentonite bed is in the range from 77 to 80 Ma, in which case our results are consistent with existing age estimates according to other sources.

130

BARABOSHKIN et al.

STRATIGRAPHY AND GEOLOGICAL CORRELATION Vol. 32 No. 2 2024

## DISCUSSION

#### On the Substage Division of the Campanian

There are proposals of a bipartite, tripartite, and quadripartite division of the Campanian stage into substages (Stratigrafiya..., 1986–1987). Following discussion and voting at the International Cretaceous Symposium in Brussels in 1995, it was recommended to subdivide the Campanian into three substages of approximately equal duration (Hancock and Gale, 1996), but there are no formal proposals to define the substages or their GSSP (Gradstein et al., 2020). In Europe, Campanian traditionally has a bipartite subdivision proposed by De Grossouvre (1901). With this division, the boundary of the substages is marked by the extinction of the belemnites Gonioteuthis auadrata (Blainville) and the appearance of belemnites of the Belemnitella mucronata group, with some overlap of their vertical distribution (Gonioteuthis quadrata gracilis/Belemnitella mucronata senior Zone: Ernst et al., 1979; Schulz et al., 1984), and the level of extinction of the genus Gonioteuthis is taken as the substage boundary (Christensen, 1997). Based on benthic foraminifers, the base of the European upper Campanian is drawn at the base of the Gavelinella monterelensis-Gavelinella costulata Zone with the almost simultaneous appearance of Brotzenella monterelensis and C. voltzianus (Walaszczyk et al., 2016).

In the North American scale, the Campanian is subdivided into three substages of approximately equal duration, which begin with the first appearance of the endemic ammonites Scaphites leei III Cobban, Baculites obtusus Meek, and Didymoceras nebrascense (Meek et Havden), respectively (Cobban et al., 2006). The base of ammonite equivalents of the North American Middle Campanian has recently been established in the section of the Severnava Sosva River on the eastern slope of the Urals (Baraboshkin et al., 2022), however, it has not yet been possible to trace it on the territory of the East European Platform and further south. In the case of a bipartite subdivision, the base of the upper Campanian approximately corresponds to the base of the "Baculites sp. (smooth)" Zone by Cobban et al. (2006), which is based on the distribution of Scaphites hippocrepis III in both regions (Ernst et al., 1979; Kennedy, 2019). Moreover, the late Campanian has a significantly longer duration than the early Campanian. According to inoceramids, this correlation is interpreted somewhat differently (Walaszczyk et al., 2016): the base of the North American middle Campanian is located within the lower part of "I." azerbaydjanensis–vorhelmensis Zone, which corresponds to the Pachydiscus stobaei/Galeola papillosa basiplana-Galerites vulgaris/Galeola papillosa basiplana Zone. Therefore, the base of the Baculites obtusus Zone should correspond to the base of the European stobaei/basiplana Zone or a higher level, i.e., it should be drawn slightly above the base of the traditional European upper Campanian. It is impossible to make a correlation with belemnites, but using benthic foraminifers this boundary in Europe coincides with the base of the Gavelinella annae Zone (Walaszczyk et al., 2016).

The position of the base of the North American upper Campanian in European sections can be determined using inoceramides (Walaszczyk et al., 2016). It is located in the upper part of the "Inoceramus" tenuilineatus Zone, which corresponds to the middle part of the Didymoceras donezianum ammonite Zone. Based on benthic foraminifers, this boundary should lie approximately within the Bolivina incrassata–Globorotalites michelinianus Zone.

In the General Stratigraphic Scale of Russia (GSS), the Campanian Stage was traditionally subdivided into two substages (*Stratigrafiya...*, 1986–1987). In its current version, the lower Campanian begins with the ammonite Placenticeras bidorsatum Zone, and the upper Campanian begins with the Hoplitoplacenticeras marroti Zone (Olfer'ev and Alekseev, 2002). These taxa, however, are not found either on the Russian Plate or in the sections on its southern periphery. The boundaries of the PF Globotruncanita elevata Zone and the nannoplankton Broinsonia parca Zone placed in the GSS also do not coincide with the substage boundaries of the Campanian and, like other paleontological boundaries, are diachronous.

A tripartite division of the Campanian stage was previously proposed for Mangyshlak sections using benthic foraminifers (Kopaevich et al., 1999) and for Campanian sections of the Russian Plate using benthic and planktonic foraminifers, dinocysts and radiolarians (Alexandrova et al., 2012a, 2012b; Guzhikov et al., 2017).

Unfortunately, this subdivision has almost no correlation with the tripartite subdivision of the North American Campanian sections, and the reference to their correspondence to "Mesozoic–Cenozoic Sequence Stratigraphy of European Basins" in (Hardenbol et al., 1998) in fact redirects us precisely to the North American scheme, designated as "informal".

The interpretation of the authors (Alexandrova et al., 2012b) of the tripartite division of the Campanian using belemnites into the lower (Belemnitella mucronata alpha (s.l.) "stage"), middle (B. mucronata mucronata) "stage", and the upper (B. langei (s.l.) "stage") is also not quite accurate, taking into account the Belemnella licharewi Zone and the fact that the Campanian-Maastrichtian boundary is now drawn on the Russian Plate within the Belemnella lanceolata Zone (Baraboshkin et al., 2019). Zonal index species of benthic foraminifers for establishing the three stages of the Campanian have been proposed differently (compare Kopaevich et al., 1999 and Aleksandrova et al., 2012a, 2021b), and strata based on planktonic foraminifers, dinocysts and radiolarians in sections in the Volga region have so far only been recognized in the rank of beds with fauna (Alexandrova et al., 2012a, 2012b).

The proposal to recognize three substages in the Campanian was discussed at a meeting on updating the GSS (Baraboshkin et al., 2013), which was developed in a short article by Seltser and Beniamovsky (2014). In it, in addition to the tripartite subdivision of the Campanian using BF, it was proposed to subdivide using ammonites found on the Russian Plate, linked to the boundaries of the belemnite zones of this region. It was proposed to place the lower boundary of the Middle Campanian at the base of the Hoplitoplacenticeras coesfeldiense and Belemnitella mucronata zones, and the lower boundary of the upper Campanian at the base of the Didymoceras donezianum and Belemnitella langei zones. At the same time, the base and top of the Campanian were not defined using ammonites. while by belemnites they coincided with the boundaries accepted for the EEP-the base of the Belemnitella praecursor mucronatiformis Zone and the top of the Belemnella licharewi Zone, respectively (Olfer'ev and Alekseev, 2005). This proposal only partially corresponds to the correlation of the same (and equivalent) zones and boundaries of the Campanian of Northern Europe and North America (Hardenbol et al., 1998; Walaszczyk et al., 2016), which, however, was recognized by the authors themselves (Sel'tser and Beniamovsky, 2014).

The listed problems make us treat the proposals for a tripartite subdivision of the Campanian with caution, although they deserve attention and further analysis.

The results we obtained (Guzhikov et al., 2021a, 2021b and this study) allow us to approach the substage division of the Campanian somewhat differently. As indicated at the beginning of the paper, we (1) adhere here to the traditional bipartite subdivision of the Campanian Stage and (2) support the proposals of the working group on the Santonian–Campanian boundary to place the base of the Campanian at the base of the magnetic chron, almost coinciding with the position of the SCBE isotopic anomaly (Gale et al., 2023). In this interpretation, the Santonian–Campanian boundary is global and isochronous for different facies (including marine and continental) sediments due to the nature of the magnetic field. Therefore, its acceptance brings more certainty to the interregional correlation of the Santonian–Campanian boundary. Using the same approach, we propose to draw the lowerupper Campanian boundary at the boundary of C33r and C33n magnetic chrons, which is discussed below.

# Correlation of the Lower-Upper Campanian Boundary Beds Using Paleomagnetic and Isotope-Geochemical Data

Currently, in the Campanian interval, corresponding in stratigraphic range to the Kudrino-1 and Kudrino-2 sections, up to 10 isotope events are identified (Jarvis et al., 2006; Thibault et al., 2016; Pearce et al., 2022). The largest of them are SCaBE (Santonian–Campanian Boundary Event), MCaE (Mid-Campanian Boundary Event) and LCaE (Late Campanian Boundary Event) (Pearce et al., 2022), equivalents of which were established in the studied sections. According to Thibault et al. (2016, text-fig. 8), the isotopic event at the boundary of chrons C33r and C33n is the "Papillosa" event, which in the Gubbio section corresponds to the maximum  $\delta^{13}$ C values at the top of the normal-polarity chron C34n (Fig. 17).

According to (Thibault et al., 2016), "Papillosa" can be traced in the Seaford Head section in England but falls on an interval of reverse polarity (according to Montgomery et al., 1998), which was identified with chron 33r in (Gale et al., 2023) is considered insufficiently substantiated. In our opinion, the identification of the "Papillosa" isotopic event in the Seaford Head section is no less controversial, since there is no information in it about the position of the boundary of chrons C33r and C33n. In the Gubbio section, the "Papillosa" event (according to Thibault et al., 2016) is located slightly below the top of the PF Globotruncanita elevata Zone. The top of the G. elevata Zone in the Kudrino-1 section is located in Member XVII and in the upper part of chron C33r (i.e., lower than in Gubbio), as well as in the BF Beds with *Bolivinoides pustulata*, overlying the Pseudogavelinella clementiana clementiana Zone and overlain by the BF Beds with Bolivinoides decorata. In the Poigny section in

2024

**Fig. 17.** Paleomagnetic and isotope-geochemical correlation of the Kudrino-1 section and bioevents with the Gubbio (Bottaccione) sections (after Thibault et al., 2016, modified), Seaford Head (after Thibault et al., 2016; Jarvis et al., 2023, modified), Poigny (after Robaszynski et al., 2005; Pearce et al., 2022, modified) Trunch and Lägerdorf (after Pearce et al., 2022, modified). **Abbreviations. Gubbio section:** D. con. = Dicarinella concavata, Rc = Radotruncana calcarata. **Kudrino-1 section:** B. p. = Bolivinoides pustulata, B. incr. = Bolivina incrassata, Bolivin. decorat. = Bolivinoides decorata, R. szajn. praecurs. = Reussella szajnochae praecursor; B. pt = Bolivinoides peterssoni. **Poigny section:** B. incr. = Bolivina incrassata. **Lägerdorf section:** s/gr = Uintacrinus westfalicus / Gonioteuthis granulata, M/gr = Marsupites testudinarius / Goniteuthis granulata, gq = Gonioteuthis granulataquadrata, li/q = Sphenoceramus lingua/ Gonioteuthis quadrataquadrata, pilula = Offaster pilula, pi/se = Offaster pilula/Galeola senonensis, senon = Galeola senonensis, papil = Galeola papillosa, co/gr = Echinocorys conica/Goniteuthis quadrata gracilis, gr = Goniteuthis quadrata gracilis, sc = Belemnitella mucronata senior, co/m = Echinocorys conica/Belemnitella mucronata, bas/spin = Galerites papillosa basiplana/ Trachyscaphites spiniger, vulgaris = Galerites vulgaris, polypl = Bostrychoceras polyplocum, langei = Belemnitella langei. Isotope events correlated after Thibault et al. (2016) and Pearce et al. (2022): Langei, Laegerdorf, Pre-LCaE, Vulgaris, Basiplana, Trunch, Papillosa, Senonensis, Mid-Campanian Event. SCBE – Santonian-Campanian, MCaE – mid-Campanian, LCaE – late Campanian. The dotted line is a correlation based on paleomagnetic data.

![](_page_44_Figure_1.jpeg)

STRATIGRAPHY AND GEOLOGICAL CORRELATION Vol. 32 No. 2 2024

France, the lower-upper Campanian boundary and the "MCaE"-Mid-Campanian event (Pearce et al., 2022) are located in the Bolivinoides decorata Zone. The "Papillosa" event in the same section is interpreted in the middle of the BF P. clementiana clementiana Zone, i.e., significantly lower than in Kudrino-1. Even if the level of occurrence of *B. decorata* is correlated in the Kudrino-1 and Poigny sections, the closest significant isotopic event will still be MCaE. which is also confirmed by the position of the level of the last presence of the dinocysts Eatonicysta? mutabilireta in the upper part of chron C33r in the Kudrino-1, Poigny and Trunch sections (Pearce et al., 2020, 2022). Based on the above, we suggest that the "Papillosa" isotopic maximum of the Gubbio section (after Thibault et al., 2016) and the MCaE of the Poigny section (Pearce et al., 2022) are the same event. With such a correlation, the boundary of the lower and upper Campanian should be drawn significantly lower than in Thibault et al. (2016). This is also confirmed by a comparison of the position of MCaE in the Gubbio section, where it is indicated near the top of the nannoplankton UC15a Zone, i.e., relatively high in the upper Campanian (Thibault et al., 2016), and in the Lägerdorf section, where this event is located above the top of the UC15a Zone.

If we follow the isotope correlation proposed in (Pearce et al., 2022), then the MCaE event traced in the Trunch section corresponds to the event of the same name according to Thibault et al. (2016) and the level of the last presence of *Gonioteuthis quadrata grac-ilis* (Stolley) in the Lägerdorf section, which looks quite plausible taking into account data from Polish sections and correlations on benthic foraminifers (Walaszczyk et al., 2016). Findings of *Gonioteuthis* in the Crimean sections are extremely rare (Iolkichev and Naidin, 1999), and their exact position in the Campanian sequence is unfortunately unknown.

Another potential level of isotope correlation is located at the top of the studied section (interval VI. Fig. 15). It corresponds to the lowest  $\delta$ 13C values and can be compared with the LCaE (Late Campanian Event) isotopic event. Although in the correlation scheme this level falls within the Beds with Bolivinoides peterssoni (BFK-9), it falls within an interval where B. monterelensis and B. decorata continue to co-occur, similar to the Poigny section, in which the Brotzenella monterelensis Zone is limited at the top by the occurrence of "Bolivina" (=Coryphostoma) incrassata (Robaszinsky et al., 2005), has a wider range. In addition, the latest occurrence of the dinocysts Palaeohystrichophora infusorioides and Exochosphaeridium? masureae in the Poigny and Trunch sections is almost similar in relation to the isotopic level of LCaE and falls at its base (Pearce et al., 2022). In the Kudrino-1 section, this event is recorded at a single level slightly below the base of the negative isotopic excursion in interval VI, which is very close to that in the mentioned sections. Unfortunately, this negative  $\delta^{13}$ C excursion has not yet been confirmed in other sections in Crimea and given that it was established on the basis of a single sample, it certainly requires additional justification. The remaining less expressive isotopic excursions are quite problematic to correlate, and are fraught with erroneous conclusions, at least until reliable isotopic data are obtained for the complete section of the Campanian of Crimea. From the correlation carried out (Fig. 17) it follows that biostratigraphic events, if compared with well-identified isochronic levels based on changes in magnetic polarity or isotopic excursions, are diachronic to varying degrees. Although this is well known (Guzhikov and Baraboshkin, 2006; Guzhikov et al., 2021b; Jarvis et al., 2023), the primary markers ("events") for most Cretaceous GSSPs are biostratigraphic (Kennedy et al., 2004, 2005; Walaszczyk et al., 2021; etc.). In this regard, we propose to change the approach to establishing the boundaries of stages and substages and draw them along the most noticeable paleomagnetic or isotopic events, near the corresponding biotic events along which these boundaries were originally outlined. De facto, this approach has already been implemented to some extent in the selection of a number of Cretaceous GSSPs (for example, Odin and Lamaurelle, 2001; Kennedy et al., 2005, 2017), in the sense that the position of the primary biostratigraphic marker is near or at the level any isotopic event.

## Proposals for Drawing the Lower-Upper Campanian Boundary

As mentioned above, the lower-upper Campanian boundary in the Russian scale is accepted at the base of the ammonite Hoplitoplacenticeras marroti Zone (Olfer'ev and Alekseev, 2003). Records of this ammonite are unknown from the territory of Russia and, moreover, are extremely rare in Europe, including the Campanian stratotype area (Kennedy, 1986). Despite the occurrence of the species in Europe (France, Spain, Portugal, Belgium, Germany), in Israel, Tajikistan, the USA, Angola and Madagascar, it is very difficult to trace the base of the upper Campanian using finds of Hoplitoplacenticeras marroti. Nannoplankton was studied from the molds of ammonites of the Marroti Zone (including the index species itself) of the type area of the upper Campanian of Aquitaine (Ariège department), which showed its assignments to the CC18B Subzone (Kennedy et al., 1992), corresponding to the UC14c Subzone of the middle of the lower Campanian (Burnett, 1998). Zone CC18 is a cooccurrence zone defined as the interval between the entry of Broinsonia parca parca (Stradner) Bukry and the disappearance of Marthasterites furcatus (Deflandre in Deflandre et Fert) Deflandre (Sissingh, 1977).

The combination of finds of *Hoplitoplacenticeras* spp. (but not *H. marroti*) and nannoplankton of the CC18c Subzone is shown for the Mizino-Lapshinovka section in the Volga Region (Olfer'ev et al., 2004). Although the nannoplankton assemblage is rightly

interpreted as Early Campanian, it is worth noting its general impoverishment.

In the Crimean sections of Kudrino-2 and Aksu-Dere, the subspecies *Broinsonia parca parca* appears in the upper part of the Santonian, in the interval of normal polarity of chron C34n, along with records of *Marsupites* (Guzhikov et al., 2021a, 2021b), while the species *Marthasterites furcatus* was not found. Thus, if nannoplankton is used as an indirect indication of the Hoplitoplacenticeras marroti ammonite Zone, the situation will become a dead end, as in this case in the Kudrino and Aksu-Dere sections this zone should be the lowermost in the Campanian.

Olfer'ev and Alekseev (2002), following Hardenbol et al. (1998), correlated the Marroti Zone is with the CC19 Zone of the Tethyan nannoplankton scale, attributed to the "late early Campanian" (Perch-Nielsen, 1985, p. 346). According to this work, the upper Campanian begins with CC21 Zone (Perch-Nielsen, 1985, p. 346), which corresponds to the middle of the upper Campanian of the GSS (Olfer'ev and Alekseev, 2002).

The above suggests that the boundaries of nannoplankton zones can have significant diachrony and, unfortunately, they are difficult to use to determine the base of the lower Campanian.

Important information about finds of *Hoplitoplacenticeras marroti* several meters above the base of the normal polarity chron C33n is provided for the Laño section in Spain (Corral et al., 2016), which confirms the proximity of the base of this chron to the base of the upper Campanian. In sections of Northern Spain, the appearance of *Hoplitoplacenticeras marroti* is accompanied by finds of the echinoid *Offaster pilula* (Küchler, 2000), but in other regions the appearance of these echinoids ("Pilula event") occurs much earlier (Fig. 17).

Specimens of *Hoplitoplacenticeras marroti* were found in Texas and Wyoming (USA) (Young, 1963; Cobban and Kennedy, 1992; Kennedy and Cobban, 2001; etc.). The specimens from Wyoming come from the middle Campanian Baculites obtusus Zone of the North American scheme (Cobban and Kennedy, 1992, p. 445) and, according to Leahy and Lerbekmo (1995) should be assigned to the middle part of reverse polarity interval C33r.

Leahy and Lerbekmo (1995, fig. 11) also show that the C33r/C33n polarity change occurs stratigraphically higher—in the middle of the Baculites asperiformis Zone. Using the co-occurrence of *Baculites obtusus* and *Hoplitoplacenticeras marroti*, the Campanian Stage of the North American scale was correlated with the European scale and divided into two parts (Cobban et al., 2006, 2008), while the substage boundary was combined with the base of the Baculites obtusus Zone and dated at  $80.58 \pm 0.55$  Ma.

Planktonic foraminifers also do not allow accurate record of the position of the base of the upper Campa-

nian, if taken at the base of the Marroti Zone. According to Hardenbol et al. (1998) and Olfer'ev and Alekseev (2002), this boundary falls on the upper part of the Globotruncanita elevata Zone but does not coincide with its top. In this case, it falls inside the reverse polarity chron C33r. In the Gubbio section, the top of the G. elevata Zone is located in the lower part of chron C33n (Coccioni and Premoli Silva, 2015), i.e., it is younger than in the sections of Central Europe (see Fig. 17). The Kudrino-1 section in this case is closer to the Central European sections.

Benthic foraminifers have already been discussed above in the corresponding section of this paper. Here we can add that in the sections of the Netherlands (Robaszynski et al., 1985), the boundary of the Campanian substages is drawn using the appearance of the belemnites Belemnitella mucronata and the BF Brotzenella monterelensis, although after a short gap and in the absence of *Hoplitoplacenticeras*. In the Poigny Borehole in the Paris Basin (Robaszynski et al., 2005; Pearce et al., 2022), the same boundary (in the original-the boundary between the lower and upper Campanian) is drawn at the base of the Brotzenella monterelensis Zone. In sections on the Russian Plate, the lowerupper Campanian boundary is drawn near the base or at the base of the B. monterelensis Zone (Olfer'ev and Alekseev, 2003, 2005; Olfer'ev et al., 2004; Beniamovsky, 2008; etc.) and is accompanied by the appearance of Belemnitella mucronata (v. Schlotheim), Belemnitella mucronata senior (Nowak), Hoplitoplacenticeras coesfeldiense and H. vari (Olfer'ev and Alekseev, 2005). Sections in the EEP show that Belemnitella mucronata mucronata and B. mucronata senior are also indicated from the lower Campanian (Olfer'ev et al., 2004, 2007a, 2007b). Note that the existence of the subspecies Belemnitella mucronata senior is generally questioned (Christensen, 1995).

In Crimea, findings of belemnites are rare, and in most cases their exact location is unknown. In the Kudrino-1 section, as already mentioned, the appearance of *Brotzenella monterelensis* biostratigraphically establishes the base of the upper Campanian, while *B. mucronata*, according to our data, appears much higher (in Kudrino-3, see description of the section).

Despite the fact that belemnites are widely used to subdivide the Campanian in northern Europe (Ernst et al., 1979; Schulz et al., 1984; Christensen, 1995, 1997; etc.), it is quite difficult to use them as a reliable marker of the substage boundary not only because of their diachronous appearance, but also because of the debatable nature of the species characteristics of Late Cretaceous belemnites and identification problems.

There are many sections in which certain biostratigraphic markers are found that claim to be used to establish the lower-Campanian boundary, however, following the information provided, all these markers are diachronous to varying degrees. Therefore, we propose to draw the boundary of the lower and upper substages of the Campanian at the isochronous level – the boundary between the C33r and C33n magnetic chrons. This level, located between samples 3169/52 and 3169/53 in the Kudrino-1 section, lies within the Beds with the BF Bolivinoides decorata (BFK-6) and Beds with Brotzenella monterelensis, Cibicides voltziana (BFK-7), located 0.5 m below the beginning of  $\delta^{13}$ C MCaE isotope event and 2.4 m above the base of the PF Globotruncana ventricosa Zone, falls in the middle of the interval with the dinocyst assemblage with Odontochitina porifera-Nelsoniella aceras (DK-3) and occupies a position within the interval of the nannoplankton UC14d–UC15d subzones. It is obvious that the Kudrino-1 section, due to the integratedity of its justification, can be a potential candidate for the limitotype of the boundary of the lower and upper substages of the Campanian, or at least an additional section to the limitotype.

In the future, if the need arises for a more refined subdivision of the Campanian Stage, there are a sufficient number of isochronous levels in the higher part of the Campanian sequence. These, in particular, include the LCaE negative isotopic excursion, which may also be present in the Kudrino-1 section, or chron C32r, which has not yet been identified in the Campanian of Crimea.

#### CONCLUSIONS

To summarize, we can draw the following conclusions.

(1) New data have been obtained for the lower part of the stratotype of the Kudrino-1 Formation, which complements previously published information on the Kudrino-2 and Aksu-Dere sections (Guzhikov et al., 2021a, 2021b). In terms of their comprehensive coverage (ammonites, belemnites, inocerams, benthic and planktonic foraminifers, nannoplankton, dinocysts, *Gilianella*, stable isotopes, paleomagnetism and radioisotope dating) they are not inferior to data from the most well-studied Campanian sections, such as Gubbio, Seaford Head, Poigny, Trunch, Lägerdorf, with which they are correlated. In the future, the results for the Kudrino section can be supplemented and detailed.

(2) The section establishes the level of the boundary of the lower and upper Campanian SSR and the European scale, confirmed by different fossil groups and other methods. Biostratigraphically, this level is most convincingly defined by a change in benthic foraminiferal associations and is based on the appearance of *Brotzenella monterelensis*, similar to sections located on the Russian Plate (Olfer'ev and Alekseev, 2003, 2005; Beniamovsky, 2008; etc.), in Western Europe (Poigny section) (Robaszynski et al., 2005; Pearce et al., 2022) and other regions.

(3) The base of the Beds with *Brotzenella monterelensis, Cibicides voltziana* (BFK-7) in the Kudrino-1 section almost coincides with the boundary of the C33r and C33n magnetic chrons and with the beginning of the  $\delta^{13}$ C MCaE isotope event. Therefore, we propose to draw the boundary of the lower and upper substages of the Campanian along the base of magnetic chron C33n. The Kudrino-1 section itself, if such a proposal is accepted, can be considered as a limitotype of the boundary of the lower and upper Campanian in GSS with its bipartite division or as an additional section to the limitotype of the ISS.

(4) Paleomagnetic and isotope-geochemical correlation made it possible to trace and clarify the boundary of the lower and upper Campanian in other well-studied sections and, in particular, to correct inaccuracies in the isotope correlation with the Gubbio section (Thibault et al., 2016). Noteworthy that despite all the advantages of correlation based on isotope-geochemical data, in some cases there are noticeable difficulties in identifying isotopic excursions. In this sense, correlation based on paleomagnetic data (provided they are well preserved) looks more unambiguous, although, of course, there may be problems here too. The use of non-paleontological methods, along with biostratigraphic ones, allows them to be complementary and generally increases the reliability of correlations, especially in regions remote from each other.

(5) The first results of U–Pb dating of zircons from the bentonite clay bed have been obtained near the interval of finds of important biostratigraphic markers – the ammonite *Pachydiscus (Pachydiscus) launayi* and inoceramids characterizing the lower Campanian Sphaeroceramus sarumensis–Cataceramus dariensis Zone. The dating refers to approximately the middle part of the BP Bolivinoides pustulata (BFK-5) Zone and the dinocyst DK-2 assemblage, as well as to the boundary interval of the PF Globotruncanita elevata and Globotruncana ventricosa zones. The weighted average concordant age for twelve zircon crystals was  $77 \pm 1$  Ma, with most crystals ranging in age from 77 to 80 Ma, further supporting the Early Campanian age of the bentonite clay interbed.

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# CONFLICT OF INTEREST

The authors of this work declare that they have no conflict of interest.

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Vol. 32 No. 2 2024

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