Sedimentogenesis in Maastrichtian-Danian basins of the Russian plate and adjacent areas in the context of plume geodynamics

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[1] The sediment composition and sedimentation conditions of Maastrichtian and Danian deposits in the vast territory of the Russian plate and adjacent regions of North Eurasia were studied. The succession of Late Cretaceous carbonaceous conditions of sedimentation in the Early Paleocene is noted in the major part of North Eurasia sedimentary basins. In some areas of the Lower Volga region and of the Northern Cis-Caspian basin, a radical change occurred in the sedimentation conditions at the Cretaceous-Paleogene boundary: Lower Paleocene siliceous formation replaced Maastrichtian carbonaceous formations. It is assumed that in this case the silica mass delivery into the basin was caused by tectonic rejuvenation of faults system at the border between the Russian platform and the Cis-Caspian basin under the large impact events. At the Maastrichtian–Danian boundary and above in the Danian, the increase of magnetic susceptibility of rocks is commonly noted for the major part at the expense of enrichment of rocks with iron in paramagnetic compounds (ferric hydrooxide and iron-containing clayey minerals) similar to metal-bearing sediments and to a lesser degree at the transport of terrigenous material addition in the period of large Early Paleocene regression. In the sediments, microspherules of metallic iron are noted that are most likely of cosmic meteoric dust. *INDEX TERMS:* 1519 Geomagnetism and Paleomagnetism: Magnetic mineralogy and petrology; 1540 Geomagnetism and Paleomagnetism: Rock and mineral magnetism; 1600 Global Change; 1749 History of Geophysics: Volcanology, geochemistry, and petrology; *KEYWORDS:* mantle plumes, K/T boundary, sediments, petromagnetism, magnetic susceptibility, paramagnetic magnetization, metallic iron, Russian plate.

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The State of the Problem

[2] As the concept of mantle plumes is formed the problem of searching for reliable criteria to identify these large sources of intraplate activity is becoming more and more actual. Among the generally accepted indicators (relief features, tectonic conditions, chemistry of magmatic rocks, geophysical anomalies, isotope characteristics), sedimentary formations are also mentioned but the problems of the plume direct influence on sedimentation actually were not discussed until recently [*Grachev,* 2000]. The activation of plume processes may indirectly affect sedimentation conditions through tectonic and geomorphologic phenomena which makes a prerequisite to discuss this problem in a slightly different context with the emphasis on comparative analysis data on the composition and mode of occurrence of preplume and plume formations of the sedimentary basin. In the zones of great effects of plumes, the differences in formations may be considered as a direct indicator of this process and in the remote areas they may bear evidence of the general tectonic and sedimentation settings in the periods of plume activity.

[3] Data on the mode of occurrence, lithology, magnetic characteristics of Maastrichtian and Danian sediments of the Russian platform, the Cis-Caspian region, the Crimea, and the Caucasus are given in this paper. These vast territories were outside the zones of direct influence of Deccan and

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North Atlantic plumes and thus may be considered as typical patterns to analyze indirect interrelations in the system "plumes – sedimentation".

Maastrichtian and Danian Sediments Composition and Mode of Occurrence

[4] The authors analysed data on the mode of occurrence, lithology and facies characteristics of Maastrichtian and Danian sediments of the vast areas of North Eurasia encompassing the territories of Lithuania, Belarus, Ukraine, lands along the Volga (Povolzh'e), the Cis-Caspian region, the Crimea, the Caucasus and Turkmenistan.

[5] At the end of Cretaceous and in the Paleocene, several large sedimentary basins were located there with individual structure-facies characteristics. The common feature of the territories is their spatial remoteness from the North Atlantic and Hindustan. Data from summarizing reports [*Nikishin et al.,* 1999] and author's data of the Caucasus, Povolzh'e, and West Turkmenistan are used in this paper.

Mountainous Areas of the Crimea, the Caucasus and Central Asia.

[6] In Central Cis-Caucasus, Danian clayey glauconite limestone and marl overlay Maastrichtian white dense limestone without apparent disconformity. Stage boundary markedly manifested in the lithology and paleontology is drawn at the base of Elburganskaya suite. Missing foraminifera and nannoplankton of zones *G. taurica* and NP1 in many areas suggest a likely hidden interruption.

[7] In Chechnya and North Dagestan, Danian sediments are missing and Maastrichtian sediments are overlain transgressively by marls of foraminefera series of the Upper Paleocene. In South (Limestone) Dagestan the boundary between Maastrichtian white limestone and Danian gray pelitomorphic limestone is uniform and pronounced. Danian base in *G. taurica* zone is not established in these sections. In Nagornyi Karabakh and East Azerbaijan, Upper Paleocene marl overlay transgressively Maastrichtian limestone.

[8] In the southern slope of West Caucasus, Upper Cretaceous and Paleogene flysch is abundant in the seaside zone from Anapa to Sochi. Maastrichtian part of flysch (Snegurovskaya suite) is composed of rhythmically alternating marl, siltstone and limestone. The boundary of the Paleogene and the Cretaceous is not marked lithologically and is only distingushed by foraminifera fauna of 50 m below the suite top. Danian lower part is not reliably established in Novorossiysk flysch.

[9] In Gornyi Crimea, Danian limestone and marl overlay Maastrichtian stage represented by sandy marl and calcareous sandstone with underwater erosion traces. In eastern Gornyi Crimea the stage boundary is concordant.

[10] In western Central Asia, sedimentation of carbonaceous type prevailed at the end of Cretaceous – the beginning of Paleogene. Maastrichtian and Danian sediments are commonly represented by limestone, marl and locally by calcareous clay.

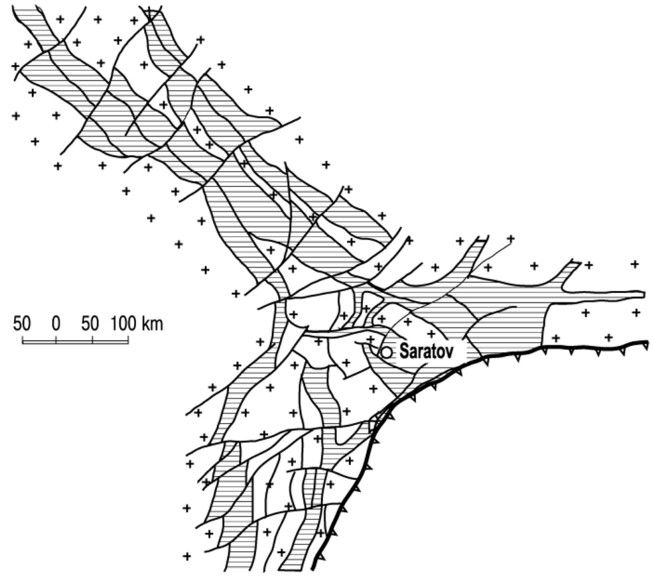


Figure 1. The tectonic scheme of Pachelmski aulocogen and its junction with on-board zone Cis-Caspian basin [*Rihter,* 2003]. The areas of aulocogen and on-board zone of the basin are shaded.

[11] In West Kopetdag, Bolshoy Balkhan and Tuarkyr, Danian sediments overlay transgressively Maastrichtian and Campanian sediments. In Malyi Balkhan, Central Kopetdag, in Mangyshlak and Ustyurt, sequences prevail that show traces of "hard ground" type interruption with insignificant stratigraphic interval. Less common are full sequences where stage boundary is marked by a thin (1–3 cm) bed of montmorillonite-hydromica brown clay. Highly metamorphosed quartz and high concentrations of Ir, Ni, Cr, Sc and platinoids were revealed in boundary clays. This layer is associated with a great impact at the end of Cretaceous – beginning of the Paleogene [*Nikishin et al.,* 1999; *Veymarn et al.,* 1998].

The Platform Areas of the Russian Plate.

[12] In Poland-Lithuania syneclise and Belorussia anteclise, Upper Cretaceous carbonaceous-terrigenous rocks shows facial changes and are complicated by numerous washouts. In many areas, Maastrichtian upper horizons and Danian stage are missing completely.

[13] In Prichenomorskaya and Dnieper-Donetsk basins and Donbass, the deposition of chalk and marl beds went on at the end of Cretaceous and the Paleocene. The boundary of the Maastrichtian and Danian is commonly erosional with missing Maastrichtian stage top completely or partially.

[14] In the central part of the Cis-Caspian basin, the Upper Cretaceous and the Paleocene are represented with limestone-marl formation. Cretaceous upper horizons are commonly washed out there and Danian sediments overlay

transgressively by Lower Maastrichtian substage sediments.

[15] Against the general relatively uniform background, the Cis-Caspian region and Povolzh'e are distinguished where a specific structure-facial zone is pronounced while it missed in other sedimentary basins.

[16] In general, in the southeastern Russian plate and on the periphery of the Cis-Caspian basin, carbonaceous sedimentation prevailed at the end of the Upper Cretaceous and in the Paleocene. The single exception was a narrow zone of contrast sedimentation of the width of 50–100 km and submeridinoal extension of more than 1000 km on Ul'yanov-Volgograd right-bank and in the onboard part of the Cis-Caspian basin. At the latitude of cities Balakovo-Volsk, a sublatitudinal branch goes off and traces eastwards to Orenburg ledge (Figure 1). Contrast combination carbonaceous and siliceous sedimentation in this zone is a feature of the geological history of Povolzh'e and the North Cis-Caspian region in the Late Cretaceous and Paleocene.

[17] A distinguishing feature is the location of siliceous beds at large disjunctive zones: sub- meridional Volga-Kama fault, Pachelmskiy aulakogen and a series of sublatitidinal step-like plunges (Zhadovskiy ledge), which bound the northern slope of the Cis-Caspian basin. Their intersection and triple junction with Pachelmskiy aulakogen is outlined at Volsk-Balakovo area. *Rikhter* [2003] was the first to determine this tectonic zone as a complex mosaic-block junction zone of three paleorifts (Figure 1). In this structure-facial zone, Cretaceous-Paleogene boundary clearly marks the end of carbonaceous sedimentation and the beginning of the Paleogene siliceous sedimentation.

[18] The first stage of siliceous sediments intense accumulation is confined to the beginning of the Santonian. Its product was Lower Santonian "banded series" represented with alternating opoka and combined clayey-siliceous, carbonaceous-siliceous and zeolitic-carbonaceous-clayey-siliceous rocks of the total thickness of up to 40 m. Rock interlayers of small thickness and mixed composition are locally encountered in the Upper Santonian, Campanian, and Maastrichtian but the bulk of them are concentrated in the Lower Santonian.

[19] The second outburst of siliceous accumulation is confined to the Zealandian. It is positioned in sections with opoka and siliceous clays of Nizhnesyzranskaya suite whose thickness reaches 50–75 m. Opoka and mixed carbonaceous-siliceous-terrigenous rocks occur as individual interlayers in Upper Paleocene and Eocene sequences [*Akhlestina and Ivanov,* 1998, 2000].

[20] The major fields of siliceous deposition are structurally attracted to the southeastern area of Ryazan-Saratov depression (Pachelmskiy aulacogen) and western and northern onboard zones of the Cis-Caspian basin. Toward the eastern slope of Voronezh massif, the opoka is replaced by terrigenous formations and in the central part of the Cis-Caspian basin by carbonaceous-terrigenous formations.

[21] In this structure-facial zone three types of boundary sections are known. The first type is well expressed in the section near village Belgorodnya, where Upper Maastrichtian limestone with sharp gap is overlapped by twelve-meter band of complex alternation of glauconite calcerous-siliceous sandstone and siltstone with gruss and rock debris basal horizon. These deposits known as Belgorodnya layers up to the section gradually change into dark gray massive opoka of Nizhnesyzrznskaya sub-suite. On a vase of nannoplankton finding of zone NP_3, *Musatov et al.* [2004] refers the Belgorodnya layers and Syzranskaya suite to the Zealandian.

[22] In the sections of the second type, Belgorodnya layers are missing and rocks of Syzranskaya suite overlay transgressively different horizons of the Maastrichtian.

[23] In the context of the question under discussion, the most interesting are sections of the third type, that is "soft ground", in which green-gray siltstones and marls of Klyuchevskaya suite overlay the uneven surface of chalk-like marls of the Maastrichtian. In contact zone, roiling and insufficient interruption traces are observed, and small rolls (up to 1 cm), white marl shapeless spots and clots of finely-dispersed carbonaceous material are noted. Below, a description is given of a section of this type located at 60 km to the northeast from Saratov in the vicinity of village Klyuchi. This section was studied in detail by *Akhlestina and Kurlaev* [1979, 1988]. Here on the hill slopes in numerous gutters and precipitous walls of ravines from bottom to top the next rocks are exposed (Figure 2).

[24] **1. The Upper Cretaceous, Maastrichtian (K_2m).** Chalk and chalklike marl light green, almost white, in large blocks with an admixture of aleurite-sandy material. Thin lenses, small rolls and green-gray carbonaceous clays aggregate accumulations of irregular form are present near the top of layer. From definitions of N. G. Muzylev, nannoplankton of zone Nethraphidites guadratus typical of the Upper Maastrichtian is characteristic of layer 1. The upper part of Maastrichtian bed ($\sim$6 m) is marked by increased carbonate content (>60% $CaCO_3$), which rapidly decreases down the section. Such a marked variability in $CaCO_3$ concentrations had been caused by Late Maastrichtian transgression, which was accompanied by warm-water Globotruncana penetration into the region [*Alexeev et al.,* 1999]. Maastrichtian sediments apparent thickness varies from 0.2–0.3 m to 10 m and more, depending on modern erosion rate.

[25] **2. The Lower Paleocene, the Danian (P_1d).** Marl is olive, greenish gray, silt, opoka-like with spot silicification which intensity increases upwards on the section. The contact with white marl of layer 1 is marked and nonuniform with traces of roiling and rewashing of underlying rocks. Numerous small (up to 1 cm) fragments and rolls of the Maastrichtian rocks are present above the contact line in green marl. Up the section carbonate content of rocks rapidly decreases from 30–40% to 5–7% and marl is replaced by silt-clayey siliceous deposits with silica content up to 70% and mixed siliceous-carbonaceous silt with SiO_2 content up to 40–50%. The thickness is 8–12 m.

[26] In the lower part of layer 2 besides Maastrichtian nannoplankton forms, species typical of the lower part of NP2 zone and are noted in some samples of zones NP1 (definitions by N. A. Savitskaya and P. G. Kalinichenko). Since the zone index species Cruciplacolithus tenuis was not detected in the samples, L. I. Ermokhina (preprint, 1990) dates this part of the section as the upper part of zone NP1 – the lower part of zone NP2. Nannoplankton of zones NP4-NP5 is

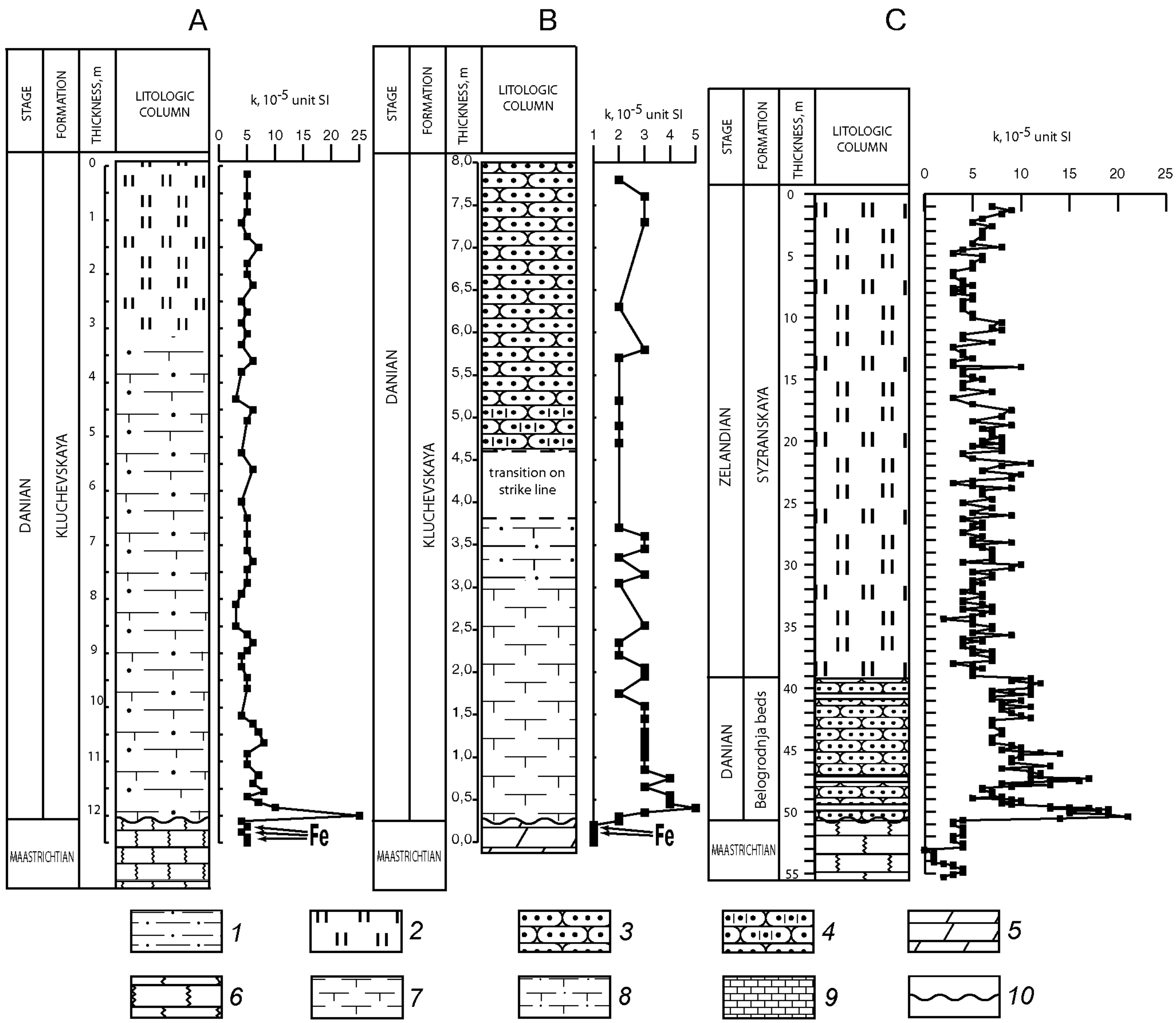


Figure 2. Magnetic susceptibility of Cretaceous-Paleogene sequences from Saratov Povolzh'e region. A – v. Teplovka, B – v. Kluchi, C – v. Belogrodnja. 1 – siltstone, 2 – opoka, 3 – sandstone, 4 – calcareous sandstone, 5 – marlstone, 6 – chalk, 7 – calcareous clay, 8 – sandy calcareous clay, 9 – limestone, 10 – gap.

defined from the upper part of layer 2. Danian section begins with the zone *Globorotalia pseudobulloides – Globoconusa daubjergensis* by the composition of plankton foraminifera complex. L. I. Ermokhina distinguished Danian sediments of layer 2 as Klyuchevskaya suite.

[27] **3. The Upper Paleocene, Syzranskaya suite (P_2sz).** Up the section, rocks of layer 2 are gradually replaced by dark gray dense opoka of Syzranskaya suite of visible thickness of 15–20 m.

[28] A similar section was studied in the vicinity of village Teplovka of Novo-Burasskiy district of Saratov region. There in the mountain slope the Upper Cretaceous–Paleocene contact is exposed in a large rain channel. The section is composed from bottom to top (Figure 2a).

[29] **The Upper Cretaceous, Maastrichtian (K_2m).** Chalk is light gray, white, soft, homogeneous. The visible thickness is 1.4 m.

[30] **The Lower Paleocene, Danian (P_1d).** Opoka are light gray, with yellowish brown shade in some places, when wet greenish, lime silt with rare dark gray spots of silica, impregnation and lenses of glauconite grains. The Paleocene sediments of Klyuchevskaya suite overlay Cretaceous weakly undulated surface. In the contact, basal layer of small thickness (0.05 m) is marked, which is represented by fragments of grayish green dense chalk. The visible thickness is 12.5 m.

[31] The literature on the problems of opal-cristobalite rock formation and mixed diversities closely related to them

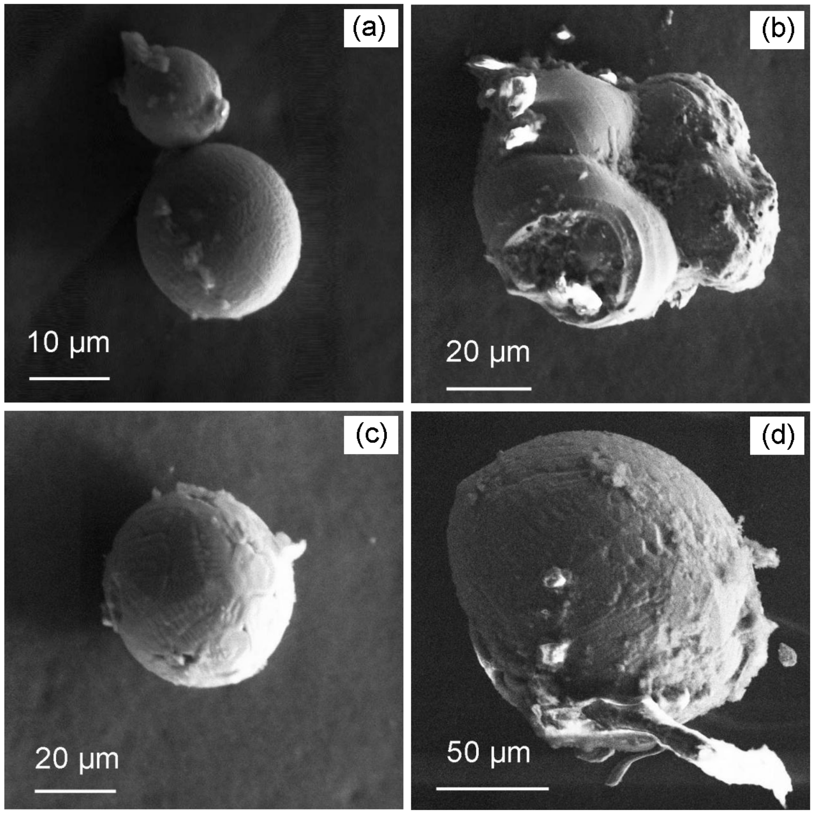


Figure 3. Iron microspherules from sediments, sections Kluchi (a, b) and Teplovka (c, d). Photos are made by V. A. Tselmovich.

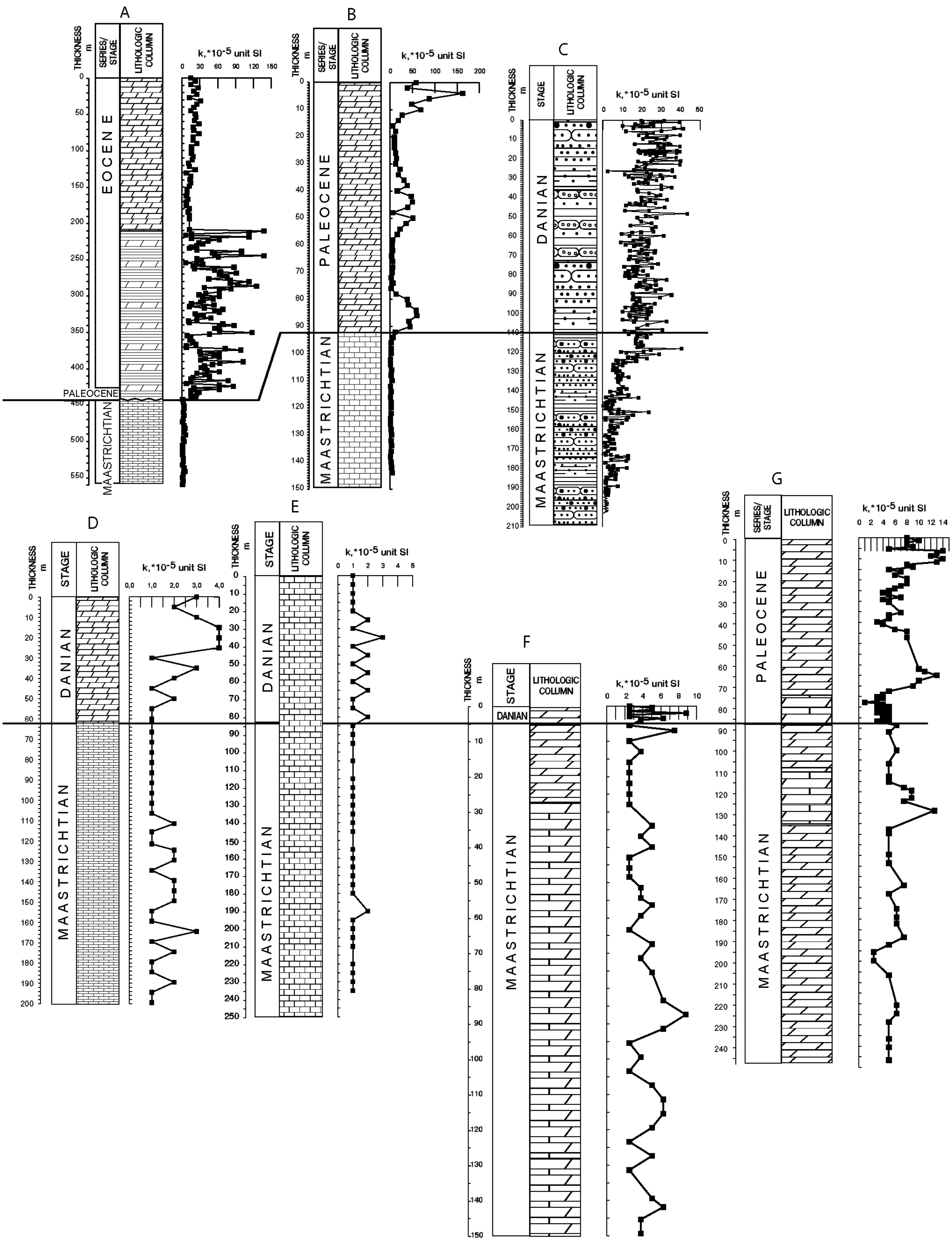
in Povolzh'e is quite extensive. Earlier, researchers associated the periodic bursts of silicic accumulation with transgressive stages of shelf basins development in the northeastern periphery of the Tethys. It was assumed that they were caused by active displacements of oceanic water masses and the rise to near-surface layers of deep water enriched with silica. Climate warming and tectonic volcanic activation favorable for plankton growth with silicic function were noted as accompanying features [*Akhlestina and Kurlaev,* 1979, 1988 and others]. Subsequently owing to evident correlation between the areas of silicic accumulation and fracture zones their formation was associated with the inflow of thermal water enriched with silica coming by deep-seated faults at the moment of their activity [*Akhlestina and Ivanov,* 2000].

[32] The association of lithotypes in the contact of Maastrichtian and Klyuchevskaya suite testify to a rapid change in sedimentation conditions with a minimum time interval or without an actual time gap. It is suggested by the marked boundary between the Maastichtian and Danian, weak traces of underwater rewashing of the soft floor, increased carbonate content of Danian low horizons with rapid growth of silicification up the section.

[33] All these features allow us to assume hidden events underlying the rapid change of sedimentation conditions in the marginal structure-facial zone. The hypothesis of tectonic activaty in the junction zones of deep-seated faults seems to be the most credible, however the initial cause of the activation has not been established.

[34] Chronologically the pulses of silicic accumulation in Povolzh'e coincided with Senomanian and Maastrichtian plumes but it can hardly testify to direct effect of the latter on the disjunctive tectonics of such a remote area. In the context of possible effects of the plumes on sedimentation, data on small pyroclastics presented in Santonian and Syzran opoka of Povolzh'e with absolute missing of it in carbonaceous parts of the section seem to bear more information [*Akhlestina and Ivanov,* 1998, 2000]. Fresh ash horizons of the type that is known in Veshenskaya suite [*Muraviev et al.,* 1997] are not of particular interest in this case because they are located close to the Caucasus and the Carpathian volcanogenic belts.

[35] Tectonic activity could have been triggered by an impact event, which occurred at the boundary of the Paleogene and the Cretaceous and whose traces in the form of a large Kamenskaya astrobleme are revealed relatively close to the lower stream of Volga (Nizhnee Povolzh'e). This hypothesis may be corroborated by numerous spherules of metallic iron of 1–10 μm in the interval from 15 cm to 20 cm in the top of the Maastrichtian immediately beneath the contact with Klyuchevskaya suite (Figure 3, see also "Magnetic characteristics"). No similar particles of metallic iron were revealed in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other stratigraphic levels of Teplovka and Klyuchi sections.

[36] The presence of metallic iron spherules of cosmic origin in sediments of different ages is a well-known phenomenon. But the our case accurately stratified isolated horizons in sections set apart for more than 30 km. Besides, data were published on the enrichment with spherules composed of hydrous ferric oxides near the Maastrichtian–Danian border in section Abat in Oman [*Ellwood et al.,* 2003]. The authors associated their appearance with a great impact event. However the interval of enrichment with spherules embraces approximately 50 cm of sediment thickness, i. e. many thousands of years and their number maximum does not coincide with K/T boundary and is 10–20 cm below it. Besides it is not clear why no spherule of metallic iron was discovered though in similar sections metallic iron spherules were repeatedly encountered. Thus in Maastrichtian–Danian sections of Koshak (Mangyshlak) and Gams (Austria) particles of metallic iron were discovered at different levels of the sections irrespective of the age and lithology of sediments [*Grachev et al.,* 2005; *Pechersky et al.,* 2006]. In these cases a relation is more likely between metallic iron particles and space meteoric dust, which subsided at different times. The data given on sections Klyuchi and Teplovka and their likely relation to impact events, owing to their spatial proximity to Cretaceous-Paleogene Kamenskaya and Puchezh-Katomskaya astroblemes, should be considered as preliminary and more detailed further studies of boundary layers and search for minerals with traces of shock metamorphism and others are required.

Magnetic Characteristics of Maastrichtian and Danian Sedimentary Rocks

[37] Paleomagnetic research of many years allowed the authors and other researchers to gather and summarize a large amount of data on scalar magnetic characteristics of rocks in reference sections of the Maastrichtian and Danian of various regions [*Ellwood et al.,* 2003; *Molostovsky,* 1986; *Molostovsky and Khramov,* 1997; *Yampolskaya et al.,* 2004 and others].

[38] In all known sections, Maastrichtian sediments are characterized by very low magnetization with its general growth in the Paleogene base. Jump of magnetization varies in a wide range and depends on the concrete geological situation. Generally two types of sequences are noted.

[39] The first type is abundant in Transcaucasian mountainous area, in southeastern Caucasus and in eastern Cis-Caucasus (Figure 4 A, B, C).

[40] In Transcausasia in Adzhi-dere section (Nagornyi Karabakh), Upper Palaeocenen terrigenous-carbonate deposits overlay Maastrichtian light gray limestone with stratigraphic unconformity. Upper Cretaceous sediments are weakly magnetic (k=1-6$\cdot 10^{-5}$ SI units), and the Paleocene top and the Eocene are distinguished in the section for their increased magnetization (k=20-140$\cdot 10^{-5}$ SI units). Cretaceous – Paleogene boundary is considerably marked if less contrasting in the magnetic susceptibility of Yunusdag Range in Northeast Azerbaijan, where Maastrichtian weakly magnetic limestone and marl (k=3-5$\cdot 10^{-5}$ SI units) are overlain by more magnetic variegated marl of the Paleocene (k varies from 20$\cdot 10^{-5}$ SI units to 162$\cdot 10^{-5}$ SI units). In the carbonaceous flysch of the Caucasus north-western termination (Novorossiysk–Anapa) susceptibility increase was established [*Guzhikov et al.,* 1998], which is minor but statistically significant at the Cretaceous–Paleogene boundary (k=1–10$\cdot 10^{-5}$–10–20$\cdot 10^{-5}$ SI units in Maastrichtian and 20-42$\cdot 10^{-5}$ SI units in the Paleogene).

[41] A feature of the first type of sections is sharp erosional boundary between systems and a considerable time gap. Susceptibility increase is caused by the ash delivery into Paleogenic basin from Transcaucasia during explosions or input of fragmental magnetic product supply from wash-down new sources.

[42] The second type of sequences is characterized by magnetic susceptibility increase, which is minor but noted everywhere near the Maastrichtian-Danian boundary; locally it is a short-time jump of susceptibility (k-peak) and in other places it is a prolonged process. Sections of Cis-Caucasus, lower Povolzh'e, Central Asia, West Europe and others (Figures 2 and 4 D, E, F, G) belong to this type.

[43] This slight magnetization increase near K/T boundary is caused by a change in sedimentation conditions and is determined by a supply of finely dispersed terrigenous material. This general manifestation of susceptibility increase is most likely caused by erosion activity revival in wash-down areas as a result of wide regression at the end of Cretaceous–the beginning of Paleogene. This manifestation is most pronounced in the sections of the shelf and the upper continental slope. From data of oceanic sediments columns [*Pechersky and Garbuzenko,* 2005], K/T boundary is frequently marked by the magnetic susceptibility peak (k-peak) but it is noted only in 30% of columns of continuous sequences including K/T boundary, i.e. for oceanic sediments it is not a characteristic of the Mesozoic–Cenozoic boundary. The distribution and value of k-peak do not depend on the distance to the nearest land, i. e. from the distance to a wash-down area. On the contrary, sediments are less magnetic in the columns that are closer to continents and susceptibility increase (k-peak) is not noted there. The value of k-peak ranges widely in agreement with lithological characteristics of sediments. The largest values of k-peak (from 60×10^{-5} SI units to 120–250×10^{-5} SI units) are located

Figure 4. Magnetic susceptibility of Cretaceous-Paleogene sequences from Caucasus and Kopet-dagh. A – Adji-dere (Fore-Caucasus, Nagorny Karabah), B – v. Yunus-dag (Eastern Caucasus, Azerbaydjan), C – v. Beta (Western Caucasus, Krasnodar region [*Guzhikov et al.,* 1998]), D – river Bass (Chechnya), E – v. Aymaki (Carbonate Dagestan), F – gorge Kanavchy (Western Kopet-dagh, Turkmenian), G – v. Kara-kala (Western Kopet-dagh, Turkmenian). The legend is the same as in Figure 2.

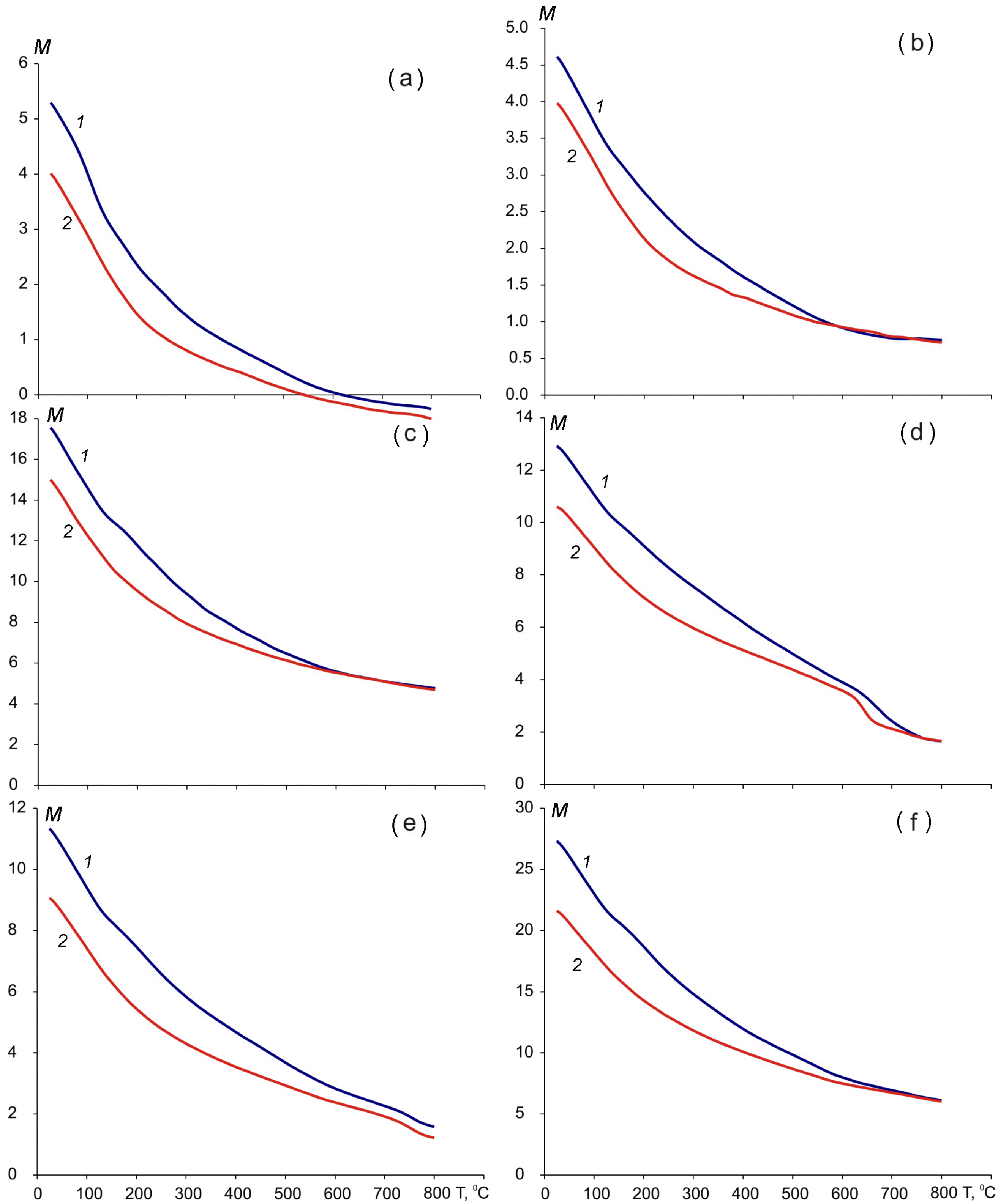

Figure 5. Examples of thermomagnetic analysis data. a–c – samples from the section Klyuchi (a, b – Maastrihtian, c – Danian), d–f – samples from the section Teplovka (d, e – Maastrihtian, f – Danian).

near the epicenters of active plumes Kergelen, Hawaii, and Whale Range. It should be emphasized that k-peaks near K/T boundaries are not unique; it is a common feature of oceanic sediments, specifically of the Upper Cretaceous and the Paleocenic. The width of k-peaks varies significantly, reflecting different time of relative enrichment of sediments with magnetic material from less than 10 thousand years to ∼0.4 million years. K/T boundary and consequently k-peak close to it are within a magnetochron of reversal polarity C29R and occupies different positions in it though they show similarity of lithology and thicknesses, i.e. biostratigraphic Maastrichtian-Danian boundary is not synchronous in the basin of the World ocean and the difference amounts to ∼0.7 million years. Non-synchronous increase of susceptibility (k-peak) and its different duration can be seen in epicontinental sediments columns (Figures 2 and 4).

[44] Thus the aforesaid on oceanic epicontinental sediments susceptibility and their lithological characteristics suggests a considerable time interval, during which magnetic minerals were accumulated at the Maastrichtian-Danian boundary and biota changes took place, rather than an abrupt "instant" jump of sedimentation changing conditions, specifically magnetic minerals accumulation at the Maastrichtian-Danian boundary. Such "duration" rules out a relation between the enumerated processes and impact events, which undoubtedly are short-lived.

[45] Let us discuss the results of detailed studies of magnetic characteristics of rocks of sections Klyuchi and Teplovka that throw light on magnetization nature of the region sediments near K/T boundary.

[46] **Klyuchi.** Material on a number of magnetic characteristics reflecting the composition and texture of magnetic minerals in Klyuchi section is uniform, which is evident from thermomagnetic analysis uniform curves (Figure 5), practically similar in Danian samples beginning with 30 cm above K/T contact and from very close values of remanent coercive force H_{cr}=33–38 mT. Thus from thermomagnetic analysis data, both Maastrichtian and Danian sediments have:

[47] a) phase with Curie point T_c=120–140°C, which disappears after the first heating. Evidently these are ferric hydrated oxides of goethite type; their contribution in magnetization amounts to approximately 10%,

[48] b) phase with T_c=200–250°C; it is most likely hemoilmenite; its contribution in magnetization is less than 20%; when a sample is heated, hemoilnmenite undergoes partial homogenization and as a result TMA curve attains hyperbolic form,

[49] c) irreversible drop of magnetization at 300–320°C that is typical of transition from maghemite to hematite,

[50] d) phase with T_c=560–590°C; it is magnetite; its contribution in magnetization is 10–30% and it is higher in Danian samples as compared to Maastrichtian sediment samples; when heated magnetite is oxidized completely or partially; maghemite disappearance and magnetite oxidization result in magnetization decrease after heating up to 800°C and it makes 0.75–0.9 of the initial value,

[51] e) phase with T_c=710–740°C; it is metallic iron with small admixtures (pure iron T_c=769°C). The latter is reliably established in Maastrichtian sediments and is practically lacking in Danian sediments. These results were supported by finds of spherules of 1–10 μm in Maastrichtian rock heavy fraction near K/T boundary (Figure 3), which were not noted in other stratigraphic layers. Microprobe analysis confirmed that it was iron.

[52] Magnetic susceptibility (Figure 2a) very low and even negative (at the expense of diamagnetic calcite) in Maastrichtian rocks and gradually increases in Danian sediments beginning with K/T boundary to 4–5×10^{-5} SI units. The jump is even more vivid in total magnetization including magnetization of magnetic and paramagnetic materials of K/T boundary: from 4.6–5.3×10^{-3} Am^2 kg^{-1} in Maastrichtian rocks to 11.6–17.6×10^{-3} Am^2 kg^{-1} in Danian rocks. It occurs first of all at the expense of considerable contribution of paramagnetic component. Thus in Danian rocks it amounts to 11.2–17.4×10^{-3} Am^2 kg^{-1} (i.e. it makes a great contribution of the total magnetization). In Maastrichtian rocks near K/T boundary it makes less than 3×10^{-3} Am^2 kg^{-1}, and at 10–20 cm below the boundary it passes into small negative values where diamagnetic component prevails and as K/T boundary has been approached against the background of this paramagnetic component increases up to its evident predominance in Danian sediments. Paramagnetic component predominance in magnetization is evident from TMA curve form resembling hyperbola (Figure 5). Paramagnetism of rocks is determined by total iron content in them. From the direct comparison [*Grachev et al.,* 2005], it follows that in upper Maastrichtian iron content in the form of Fe_2O_3 is less than 0.5%, where as in Danian base it is 2–3.5%. Since composition and coercivity of magnetic minerals are close on the whole section, we may assume that the saturation remanent magnetization of rocks in the section is only determined by magnetic mineral concentration. In Maastrichtian rocks it varies from 0.014–0.015×10^{-3} Am^2 kg^{-1} to 0.029–0.042×10^{-3} Am^2 kg^{-1}, the jump is not great but it is significant and it gradually increases up the section (Figure 6). Thus judging by magnetic characteristics Maastrichtian sediments differ from Danian sediments first of all by the total iron content as well as by a small change in the total content of magnetic minerals and presence of small concentrations of metallic iron in the top of Maastrichtian sediments.

[53] **Teplovka.** The material is considerably uniform by magnetic characteristics, even more uniform than in Klyuchi section in both composition of magnetic minerals (thermomagnetic analysis data, Figure 5) and their structure (remanent coercivity varies in a narrow range from 39 mT to 42 mT). It is evident from susceptibility behavior as well (Figure 2).

[54] From thermomagnetic analysis data, Maastrichtian and Danian sediments of Teplovka section contain similar minerals as in Klyuchi section:

[55] a) ferric hydrated oxides of goethite type (T_c=110–140°C, which disappear after the first heating of the sample), their contribution in magnetization is approximately 10%,

[56] b) hemoilmenite (T_c=210–270°C), its contribution in magnetization is less than 20%, when samples are heated hemoilmenite undergoes partial homogenization and as a result TMA curve takes the hyperbolic form,

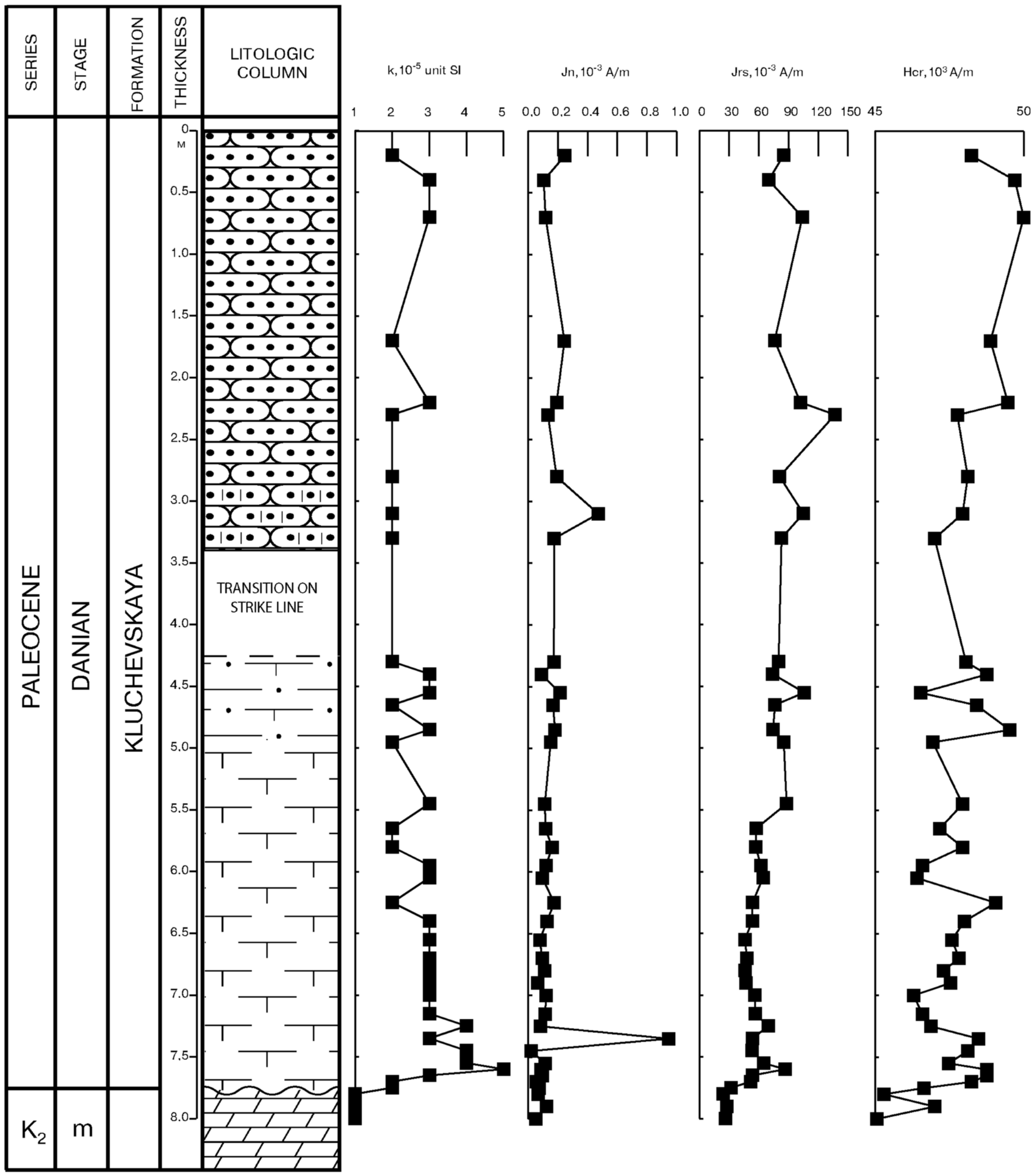

Figure 6. Some magnetic properties of sediments from Klyuchi section.

[57] c) irreversible drop of magnetization at 300–320°C, typical of maghemite transition into hematite,

[58] d) magnetite (T_c=560–590°C), its contribution in magnetization is 20–40%, when heated, it is partially or completely oxidized, disappearance of maghemite and magnetite oxidization result in magnetization decrease when it is heated up to 800°C (0.76–0.95 of initial value),

[59] e) metallic iron (T_c=730–770°C), the latter is established in Maastrichtian sediments and is not revealed in Danian sediments, iron contribution in magnetization ranges from 5% to 50% (Figure 5), maximum is at 30 cm below the contact with Danian sediments. Value of saturation magnetization in this point is 6×10^{-3} Am^2 kg^{-1}, iron saturation magnetization is $\sim$200 Am^2 kg^{-1}, and correspondingly metallic iron content is 0.003%. Numerous magnetic spherules of metallic iron of 1–10 μm (Figure 3) were extracted from heavy fraction of Maastrichtian rocks samples near K/T boundary, which is supported by microprobe analysis data.

[60] As distinct from Klyuchi section, magnetic susceptibility does not increase gradually in the transition from Maastrichtian sediments to Danian sediments. In section Teplovka above the K/T contact, a narrow peak of magnetic susceptibility is noted; above and below it, mag-

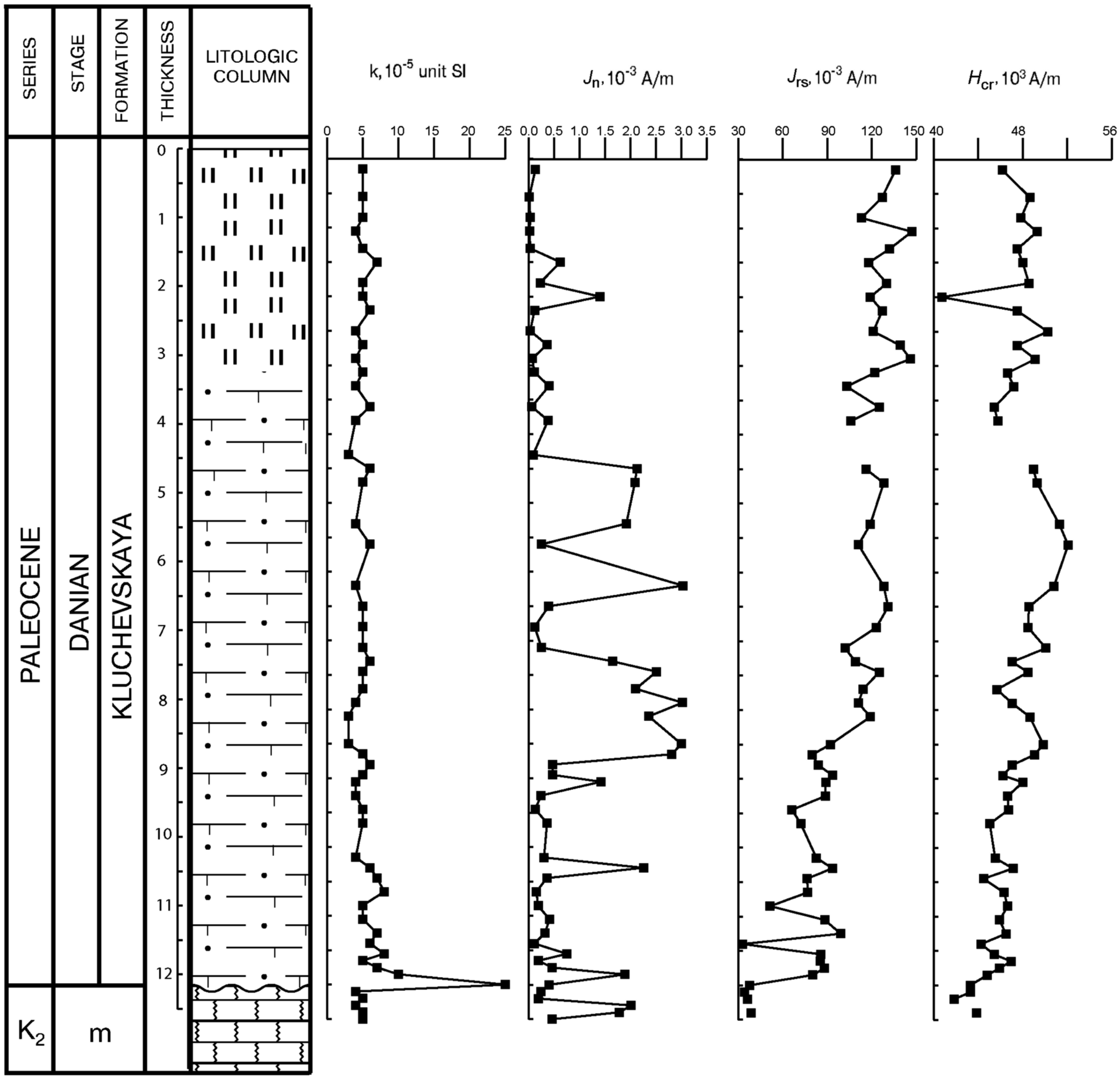

Figure 7. Some magnetic properties of sediments from Teplovka section.

netic susceptibility value is similar on the whole section (Figure 2a) and it is somewhat higher than in section Klyuchi. Total and paramagnetic magnetization behave in the same way: the former varies in a small range from 11.2×10^{-3} Am^2 kg^{-1} to 13.4×10^{-3} Am^2 kg^{-1}, against it a peak up to 40×10^{-3} Am^2 kg^{-1} is noted above the contact and a quick drop to background level at the first tens of cm; paramagnetic magnetization "background" is 6–7×10^{-3} Am^2 kg^{-1} in Maastrichtian sediments and 9–11×10^{-3} Am^2 kg^{-1} in Danian sediments and the peak reaches 35.7×10^{-3} Am^2 kg^{-1}. That means that similar to Klyuchi section, the paramagnetic component makes a considerable part both of the peak and background value of magnetization, which is manifested in the form of TMA curves, which is close to hyperbolic (Figure 5). But the general level of magnetization is considerably higher than the rocks of Klyuchi section. In Teplovka section, iron content (Fe_2O_3) is 1–1.5% in Maastrichtian "background", approximately 2% in Danian "background" and "the peak" of content is 7%. A higher "background" iron content influenced the Teplovka rock susceptibility higher level. As distinct from the general (paramagnetic) iron content, magnetic mineral content behaves in a different way. It resembles Klyuchi section, which can be seen from the behavior of saturation remanent magnetization (Figure 7) depending on magnetic mineral content. Generally, magnetic mineral content in Teplovka section is considerably higher than in Klyuchi section. In Maastrichtian sediments, J_{rs}=0.023–0.04×10^{-3} Am^2 kg^{-1}, in Danian sediments, near the contact, it is 0.045×10^{-3} Am^2 kg^{-1}, and up the section, 30 cm higher, J_{rs} rises up to 0.076×10^{-3} Am^2 kg^{-1} and then gradually increases with some variation (Figure 6) actually similar to Klyuchi section.

[61] Thus the impression is formed that the flash of magnetic susceptibility near K/T boundary was not caused by a single event but resulted from close in time but not synchronous events of iron accumulation in paramagnetic minerals in sediments that is ferric hydroxide and clayey minerals containing iron. It resembles the formation process of metal-bearing sediments and ferrous microconcretions, which is a result of volcanic and hydrothermal activity [*Gurvich,* 1998]. This process differs essentially from terrigenous accumulation of magnetic minerals; the series is identical in both Maastrichtian top and Danian low part; their concentrations somewhat vary from the Maastrichtian to the Danian.

Conclusion

[62] The general trend in sedimentation development is the inherited character of carbonaceous deposition in the major part of sedimentary basins at the end of Cretaceous–beginning of the Paleogene. Limestone-marl formation of the Upper Cretaceous developed in the Early Paleocene as well. An exception was the margin of southeastern ending of the Russian Plate and the Cis-Caspian Basin with its sharply contrasting sedimentary settings at the Maastrichtian–Danian boundary. There are good reasons to believe that a rapid transition from Late Cretaceous carbonaceous sedimentation to silicious accumulation in the Early Paleocene for the major part was caused by the arrival of silica and iron paramagnetic compounds, which came by faults in the periods of their tectonic activation.

[63] From literature and direct observations, the Maastrihtian–Danian boundary in vast areas is marked by low but stable growth of sedimentary rocks susceptibility at the expense of a supply of fine volcanogenic-terrigenous material for the major part paramagnetic (iron hydroxides and clayey minerals containing iron). The stability of this feature in the sections of shelf and upper continental slope is remarkable. This minor rise of magnetization at the boundary between two systems may be interpreted as the initial stage indicator of large-scale changes in sedimentation processes at a large part of the earth surface, including volcanogenic and hydrothermal processes that resulted in the accumulation of metal-bearing sediments and concretions. It is conceivable that a deep relation may have existed between these processes and large geodynamic events, which also included plume formation processes as a part, in the Mesozoic–Cenozoic boundary.

[64] From correlation of available data, tectonic settings of areas related to plumes and of areas located out of zones of their direct influence appear to be somewhat antipodal. The former are characterized by lacking differentiation of tectonic movements, and scarce troughs only show subsidence of small amplitudes. On the contrary, in remote areas, sedimentation in the Late Cretaceous and Early Paleogene was characterized by lateral heterogeneity, frequent facies alteration, numerous erosions, breaks in sedimentation and common erosional unconformity in the Maastrichtian–Danian boundary. Sections that show gradual transition from the Maastrichtian to the Danian are exclusively rare; in this case hidden interruptions in them are not excluded. The cause of such differences is not evident and thus we restrict ourselves to stating them.

[65] At present the evidence of the plumes direct influence on sedimentary formations of remote areas is not convincing. Dispersed volcanogenic material admixtures in beddings formed in the epochs of plume process may become perspective indicator. It is not improbable that they may occur in the siliceous deposits of Povolzh'e. Such indicator may be the increased accumulation in sediments of iron-containing paramagnetic minerals of volcanogenic hydrothermal origin of the type of metal-bearing sediments. It awaits for special directed research. Several thin horizons with ash and vitroclastic material in Santonian and Zealandian opoka beds testify to prolonged volcanic activity outside Povolzh'e. In principle, such activity may be related to plumes, but it is not inconceivable that the other feature, island-arc volcanism in Transcaucasia was superimposed.

[66] An illustrative example shows the lack of direct relation between plume (magmatic) activity and impact events. From detailed biostratigraphic, geochemical and petromagnetic data on the transition layer of clay between the Maastrichtian and the Danian in Gams section (East Alps, Austria) [*Grachev et al.,* 2005], it was established that the early stage of its accumulation went on with active basalt volcanism and it was approximately 500–800 years later, at the end of the layer accumulation, that the impact event indicators like local accumulations of metallic nickel and ferro-nickel alloy spherules and diamond crystals appeared.

[67] In the Upper Maastrichtian sediments microspherules of metallic iron are noted that are most likely of cosmic meteoric dust, and have no direct relation to impact or/and plume events.

[68] On the other hand, a marked chronological coincidence of numerous plume activity with global events levels in the Phanerozoic is significant. Such relation is noted at the Vendian-Phanerozoic boundary as well as at the Paleozoic-Mesozoic, the Mesozoic-Cenozoic, and the Eocene-Oligocene boundaries. These facts cannot be explained by a coincidence. They suggest a relation between plume process and large geodynamic reconstructions at major geohistorical boundaries in the last 600 million years.

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