quaternary

Article

Buried River Valleys of the Neogene and Early Quaternary in the Middle Volga Region, European Russia

Elena V. Petrova [1], Artyom V. Gusarov [2,*] and Achim A. Beylich [3]

[1] Institute of Environmental Sciences, Kazan Federal University, 420008 Kazan, Russia; helengeo@mail.ru
[2] Institute of Geology and Petroleum Technologies, Kazan Federal University, 420008 Kazan, Russia
[3] Geomorphological Field Laboratory (GFL), 7584 Selbustrand, Norway; achim.beylich@gmail.com
* Correspondence: avgusarov@mail.ru

Abstract: Buried river valleys from the Neogene–Quaternary time are widespread throughout the Middle Volga region of the Russian Plain. They have been studied for a long period, since the 1940s, with the last major generalizations dating back to the 1980s. This paper presents new results based on GIS mapping using materials from the state geological study of the region in 1960–1970, 1984–1996 and 2000–2002. On the whole, the pattern of the buried valley network is close to the modern valley network of the region. During the Quaternary, the right-sided displacement of the valley incisions prevailed. The incisions of modern river valleys are located above the Neogene (pre-Akchagyl) incisions almost throughout the entire territory. The vertical displacement amplitude ranges from 30 to 200 m. The morphometric characteristics of the paleovalleys (the depth and width of the incisions, as well as the gradients of the bottoms of the paleovalleys) exceeded modern ones. The maximum values were typical for the middle Paleo-Volga valley: the width of the valley reached 10 km, the incision depth was −201.4 m below sea level and the bottom gradient was 0.9–5.0 m/km. The most important factor that influenced the position of paleovalleys and their morphological appearance was fluctuations in the level of the Caspian paleowaterbody. According to this study, the development of paleovalleys began in the Miocene and ended in the Early Quaternary. The alluvial–lacustrine type of sedimentation was predominant. The results of this work contribute to the study of the paleogeography of the Cenozoic of the southeast of the Russian Plain.

Keywords: paleoriver; paleovalley; valley incision; sedimentation; alluvium; valley morphometry; Miocene; Pliocene; Pleistocene; Akchagyl; Kama River; Caspian Sea; Russian Plain

Citation: Petrova, E.V.; Gusarov, A.V.; Beylich, A.A. Buried River Valleys of the Neogene and Early Quaternary in the Middle Volga Region, European Russia. *Quaternary* **2023**, *6*, 29. https://doi.org/10.3390/quat6020029

Academic Editors: James B. Innes and Marcello Tropeano

Received: 8 March 2023
Revised: 17 April 2023
Accepted: 25 April 2023
Published: 30 April 2023

1. Introduction

The buried erosion relief has been the subject of study since the late 19th century. Thus, Trautschold [1] and Nikitin [2] gave a description of erosion hollows in the Carboniferous deposits of the Moscow region (European Russia) and Thomas [3] and Bridge [4] in Canada. The history of studying the buried river valleys of the Volga region began with research within the Middle Volga region, which is the confluence of the two largest rivers in Europe–the Volga and Kama rivers. The study of the network of ancient valleys was inextricably associated with the history of the study of the Neogene–Quaternary deposits of this territory. After the publication (in 1843) of an article by Yazykov [5] on the existence of sandy-argillaceous deposits with freshwater fauna within the left bank of the Kama River (Kazan province of the Russian Empire), which he called deposits of the "Bulgarian waterbody" ("Bulgarian basin"), there was a long discussion about the genesis of these deposits. Eichwald [6] and Golovkinsky [7] attributed the deposits of the Bulgarian waterbody to marine, or rather to the "Caspian", formations; Shtukenberg [8] singled out freshwater formations from the Caspian ones. Krotov and Nechaev [9] described the marine fauna of the "Caspian" type within the Bulgarian waterbody and attributed the deposits to supra-Tertiary formations.

Rosen [10] expressed a different point of view. In his opinion, the deposits spread south of the Kama River along the left bank of the Volga River were formed as a result of ancient floods of these rivers and were of alluvial origin. Nikitin [11] mapped both marine "Caspian" and freshwater deposits in the Cheremshan and Sulcha river basins, which, in his opinion, are riverine. He determined the age of the deposits as the end of the Tertiary and the beginning of the post-Tertiary. Thus, by the end of the 19th century, not only marine but also freshwater alluvial deposits belonged to the so-called "Caspian" formations. The works of Andrusov [12], Pavlov [13] and Mazarovich [14] laid the foundation for the stratigraphic subdivision of the Neogene and Quaternary deposits of the region. In the 1930s–1940s, the confinement of these deposits to ancient river valleys became more and more obvious. In the 1930s, two erosion incisions (paleochannels of the Volga River) were discovered near the city of Kazan. The age of one of these incisions was determined by Tikhvinskaya [15] as Pliocene. The first schematic location of the valley of the ancient Kama River within the study area was given by Rozanov in 1948 [16]. Based on geophysical data, Rozanov meridionally traced the paleochannel of the Kama River from the city of Chistopol to the mouth of the Sok River. Kirsanov [16] combined sub-Akchagyl freshwater sediments to the "Balakhani Stage" and traced the distribution of deposits of this stage along the valleys of the Kama River and its tributaries—the Sheshma, Zay, Sulcha and Cheremshan rivers. Kashtanov [16] restored the location of the Paleo-Kama River valley based on more than 300 geological wells.

A fundamental study of the ancient valleys of the Volga-Kama region is Goretsky's monograph [16]. This monograph laid the foundations of the paleopotamological method in the study of buried river valleys and gave a modern regional stratigraphic subdivision of the Neogene deposits of the Volga–Kama region. A significant contribution to the stratigraphy of the Neogene of the Middle Volga region was also made by Kirsanov [17]. In the 1970s–1980s, generalizing works on the evolution of river valleys in the Middle Volga region and Cis–Urals region [18–20] were published.

In the 2000s, during the state geological survey for the purpose of additional study of the territory of the Middle Volga region, extensive borehole and cartographic material appeared. There were also changes in the stratigraphy of the Neogene and Quaternary systems to the southeast of the Russian Plain (or East European Plain), which made it necessary to revise the history of the development of the paleovalleys of the Middle Volga region. New geological data made it possible to trace the position of Neogene–Quaternary paleovalleys, expand our understanding of their morphology and morphometry and take a fresh look at the history of their development. This study was written based on the analysis of materials from the state geological survey of the region from the 1960s to the 2000s and references stratigraphic sections.

In addition to the scientific interest associated with the reconstruction of the history of the development of the network of river valleys in the study region in the Neogene and Early Quaternary and a certain contribution to the study of the paleogeography of the Cenozoic of the east of the Russian Plain, the study of buried valleys is also of applied importance. This is due to the fact that buried river valleys are closely associated with deposits of sandy-clay building materials and are accumulators of fresh groundwater; their features must also be taken into account in the construction of hydraulic structures, industrial infrastructure, etc.

2. Materials and Methods

2.1. Study Area

The Middle Volga region (more precisely, the Middle Volga region and Lower Kama region) is located in the east of the Russian Plain, at the confluence of the largest rivers of Eastern Europe: the Volga River and the Kama River (Figure 1). The nature of the relief of the territory is determined by the alternation of denudation-tiered uplands and accumulative lowlands [21]. The largest uplands of the region are the Volga Upland, Bugulma–Belebey Upland and the Vyatsky Uval. The Volga Upland (up to 381 m within the Zhiguli, a mountain-like elevated massif within the Volga Upland) enters this territory with its northeastern part. Its watershed spaces are flat-convex hilly surfaces. The relief features of the Bugulma–Belebey Upland, located in the southeast of the territory under consideration, are generally similar to the Volga Upland. This upland is characterized by flatter watershed surfaces and higher absolute elevations (more than 380 m). The Vyatsky Uval (up to 284 m) is a submeridionally elongated upland that enters the study area only at its southern end. A common feature of the relief of these uplands is the presence of several altitudinal levels. The two upper levels (280–320 m and 180–240 m a.s.l.) are associated with the stages of denudation leveling (planation) of the territory. The lower relief level (160–180 m a.s.l.) is a polygenetic planation surface [22,23].

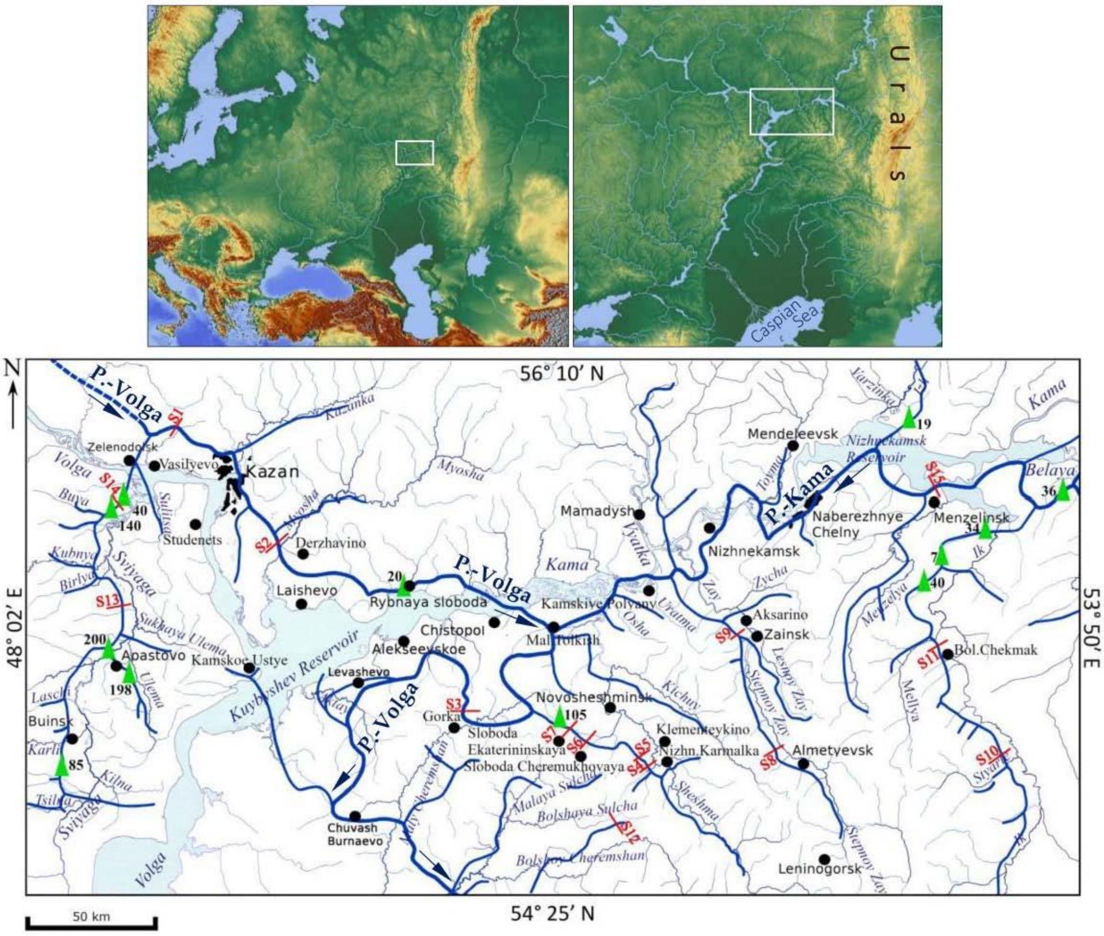

Figure 1. Location of the studied key (reference) geological wells and geological profiles in the Middle Volga region (within the border of the Republic of Tatarstan, European Russia). S3 and 200 are, respectively, reference geological transverse profiles (sections) (in red) and reference geological wells (green triangles) of the Middle Volga series of geological study sheets. The pale blue solid lines are the modern river network; the dark blue solid lines are the reconstructed axial zones of the buried river valleys of the Neogene and Early Quaternary (according to [24] with some changes): P.-Volga—the Paleo-Volga River, P.-Kama—the Paleo-Kama River (arrows show the direction of flow of these paleorivers); the dark blue dotted line is the assumed position of the axial zone of the buried paleovalley of the Volga River; the black circles are settlements.

The uplands are separated from each other by lowlands, the formation of which was associated with the geological activity of the large rivers of the region. The most extensive of them are the Trans-Volga (Zavolzhskaya) Lowland and the Kama–Belaya Lowland. The Trans-Volga Lowland is best expressed south of the mouth of the Kama River. To the west of the city of Kazan, it stretches in a relatively narrow strip along the middle Volga River valley. The average elevations vary from 100 to 120 m. The minimum absolute elevation of the land surface is confined to the level of the Kuybyshev Reservoir, the long-term average level of which is 53 m.

At present, the study area is dissected by an extensive network of river valleys and small dry valleys. The largest rivers in the region are the Volga, Kama, Vyatka and Belaya. A feature of the modern network of valleys is a well-defined floodplain and a complex of river terraces; river valleys are asymmetrical.

2.2. Materials

The work is based on data from the state geological survey of the Middle Volga region (within the administrative border of the Republic of Tatarstan, Russia) for different years (1960–1970, 1984–1996 and 2000–2002). The main source of information is the materials of the Federal Budgetary Institution "Territorial Fund of Geological Information for the Volga Federal District". Information processing was carried out using GIS mapping methods. The work also used information from published literary sources.

2.3. Methods

This study was carried out based on a database of geological wells that penetrated the Neogene–Quaternary deposits, as well as an earlier reconstruction of the position of Neogene–Early Quaternary paleovalleys using GIS mapping methods [24]. This made it possible to operate with diverse geological materials to assess the morphological and morphometric characteristics of paleovalleys and the magnitude of the displacement of paleoincisions and also made it possible to trace the features of the development of paleovalleys at various time stages.

Let us briefly characterize the creation of the database and cartographic material, which served as the basis for this study. The database was created in the MapInfo 6.0 program and includes 1465 wells, 986 of which penetrated the entire thickness of the Neogene–Quaternary deposits that fill the paleovalleys. It contains information about the location, the absolute elevation of the wellhead and base of the Neogene deposits and individual stratigraphic units (layers) and the total thickness of the Neogene–Quaternary deposits.

Reconstruction of the position of paleovalleys was carried out using the methods of geoinformation mapping. Information processing was carried out using the MapInfo 6.0 and Surfer 8.0 software packages, which are widely used for geological data processing and relief reconstruction. This work also used the cartographic material of the geological survey at a scale of 1:200,000, which made it possible to identify the boundaries of the distribution of Neogene deposits within the study area.

The original database of geological wells and the identified boundaries of the Neogene deposits were entered by "Surfer 8.0". Using various methods included in the Surfer 8.0 software package ("Minimum curvature", "Moving average", "Natural Neighbor", "Nearest neighbor", "Polynomial regression", "Radial basis function", "Local polynomial" and "Krigging"), digital models of the thickness distribution of the Neogene–Early Quaternary deposits and the erosion surface buried under the Neogene deposits were built. Modeling was carried out within the contour of the distribution of Neogene deposits, with a step of nodes from 25 to 50 m, followed by verification of the modeling results in selected key areas with the largest number of wells per unit area. The most optimal processing method was "Krigging" [25], which was used to obtain distribution models and raster images of the above values.

The simulation data were transferred to the MapInfo 6.0 program. Based on these data, digital maps (1:200,000) of the thickness of the Neogene deposits and the erosion surface buried under the Neogene deposits were built. When constructing maps, the modeling data were corrected considering the wells that were not included in the digital models (wells that did not pass through the entire Neogene deposits thickness) and also refined at control points with the maximum concentration of wells. According to the map of the erosion surface buried under the Neogene deposits, the position of paleovalleys in the region was reconstructed [24]. The obtained cartographic arrangement of paleovalleys allows for profiling of the sections of paleovalleys and estimating of the values of paleovalleys displacement relative to modern valley incisions.

Since the database, created in MapInfo 6.0 by a single well numbering, was linked to a catalog of wells with a full description of the sections, this allowed for a selection of wells for subsequent research purposes. The transverse profiles of paleovalleys were built in areas with the highest concentration of wells, taking into account the stratigraphic completeness of the sections. In the course of the work, geological wells (about 80) with the most complete stratigraphic subdivision were selected. All wells were coordinated with the Goretsky scheme [16] since it was this scheme that formed the basis of all regional schemes and further to the modern regional scale.

An analysis of the borehole material of transverse profiles within various areas of the paleovalleys of the study area made it possible to trace the features of their development during the Neogene–Early Quaternary time. The history of the development of river paleovalleys of the Middle Volga region was considered in relation to the modern regional scale. The reference geological wells (12 units) were the wells of the state geological survey on the Middle Volga region [26] (Figure 1). Thus, the database created based on GIS mapping makes it possible to obtain certain characteristics of paleovalleys, depending on the objectives of the study.

3. Results and Discussion

3.1. Characteristics of the Buried Neogene–Early Quaternary River Valleys of the Study Region

3.1.1. Location of Paleovalleys

Buried river valleys are widespread throughout the Middle Volga region. In this study, only the paleovalleys that formed in the Neogene are considered. In the Late Neogene (Pontus), the valleys of almost all large and medium-sized rivers that currently exist were formed (Figure 1). The main rivers at that time were the Paleo-Belaya River (the largest river) and the Paleo-Volga River. However, since the name Paleo-Kama appears more frequently in the scientific literature than Paleo-Belaya, we also use the name Paleo-Kama.

The Paleo-Kama River valley is traced from the modern mouth of the Belaya River, except for several sections of the valley, along the left bank of the lower Kama River towards the village of Biklyan and further to the village of Mal. Tolkish, where the confluence with the Paleo-Volga took place. The maximum incision depth of the Paleo-Kama River in the area near the village of Mal. Tolkish (Figure 1) is −113.8 m below sea level.

The largest rivers flowing into the Paleo-Kama from the south were Paleo-Ik (with a tributary of the Paleo-Mellya River) and Paleo-Zay. Significant tributaries were the Paleo-Menzelya and Paleo-Kichuy. From the north, Paleo-Izh, Paleo-Toyma and Paleo-Vyatka flowed into the Paleo-Kama River. All paleovalleys of the southern tributaries (except for the middle reaches of the Paleo-Menzelya River), as well as the Paleo-Vyatka valley, are mapped along the left bank of modern rivers. The Paleo-Volga can be traced along the left bank of the modern Volga River valley. In the section Zelenodolsk–Chistopol, a number of large tributaries (Paleo-Sviyaga, Paleo-Kazanka and Paleo-Myosha) flowed into the Paleo-Volga River. After the confluence with the Paleo-Kama River, the Paleo-Volga River, forming arms, can be traced from Levashevo to Chuvash Burnaevo and further to the Bolshoy Cheremshan River valley. The maximum incision depth in the study area is fixed at −201.4 m below sea level nearby Chuvash Burnaevo (Alkeevsky district of the Republic of Tatarstan) (Figure 1). On the left bank, the valleys of its large tributaries such as Paleo-Bolshoy Cheremshan, Paleo-Maly Cheremshan and Paleo-Sulcha rivers are mapped.

Most of the paleovalleys are located to the left of the modern valleys and this is more noticeable for the rivers of submeridional strike (Figure 1). Such a displacement was associated, first of all, with the influence of the Coriolis force (in the Northern Hemisphere of the planet, regardless of the direction of flow, moving water flows tend to deviate to the right; the exception is the areas of paleovalleys, where other factors predominate, primarily tectonics, as well as rock lithology); this influence was the higher, the greater was the water flow. The same trend can be traced, most likely, in the Lower Don River of the Russian Plain. However, throughout the rest of the paleovalley of the Don River, this trend is not traced, since the history of the Paleo-Don River was longer and numerous rearrangements took place in its basin, primarily associated with fluctuations in the vast Eastern Paratethys waterbody [27].

Assessing the displacement of modern valley incisions relative to paleoincisions showed that right-sided displacement prevailed in the study area. The largest displacement during the Quaternary period was typical for the Volga River. On average, this displacement was 30–50 km and the maximum was about 100 km. The displacement of large tributaries of the Volga River and the Kama River, as a rule, did not exceed 8–10 km, except for the lower reaches of the Sheshma River, where the maximum value (35 km) was recorded (Figure 2).

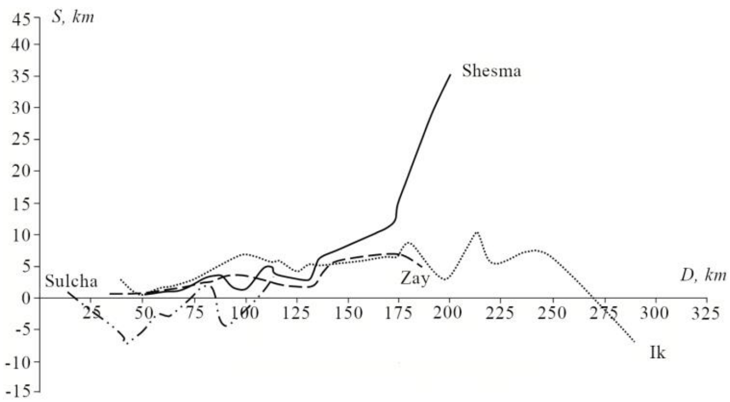

Figure 2. Quaternary displacement of the Sheshma, Zay, Ik and Sulcha rivers (see Figure 1). *D*—the distance along the axial zones of the paleoincisions of the rivers; *S*—the displacement of the modern channels of the rivers from the axial zones of their paleoincisions.

The maximum displacement of the lower Kama River did not exceed 10–12 km, and in some areas, the modern channel of the lower Kama River is located above the paleochannel or even to the left of it. This feature of the lower Kama River is due to several reasons. The origin of the lower Kama River valley in its lower reaches was determined by the position of the Kama-Kinel fault system. In hydrographic terms, the modern lower Kama River forms significant meanders, which in some areas resulted in a left-sided displacement of the modern incision. The displacement of modern river valleys relative to their Neogene paleoincisions was also affected by the lithological factor [24].

3.1.2. Morphology and Morphometry of Paleovalleys

A feature of the morphology of the paleovalleys of the study region is a deep valley incision and the absence (highly likely) of a terrace complex (Figures 3 and 4). The appearance of the valleys was primarily determined by the size of the watercourse and the lithology of the host rocks, as well as fluctuations in the level of the Caspian Sea. The width of the paleovalley of the Volga River reaches 9–10 km in some areas, while the width of the pre-Akchagyl incision does not exceed 3–4 km. The paleovalley of the lower Kama River is narrower; its width in the study area does not exceed 3 km, while the width of the pre-Akchagyl incision is no more than 1.5 km. The upper sections of the valleys in the lower reaches of many tributaries are of considerable width. This was due to the lateral erosion of the valleys during the maximum transgression of the Caspian Sea. Table 1 shows the morphometric characteristics of some paleovalleys studied.

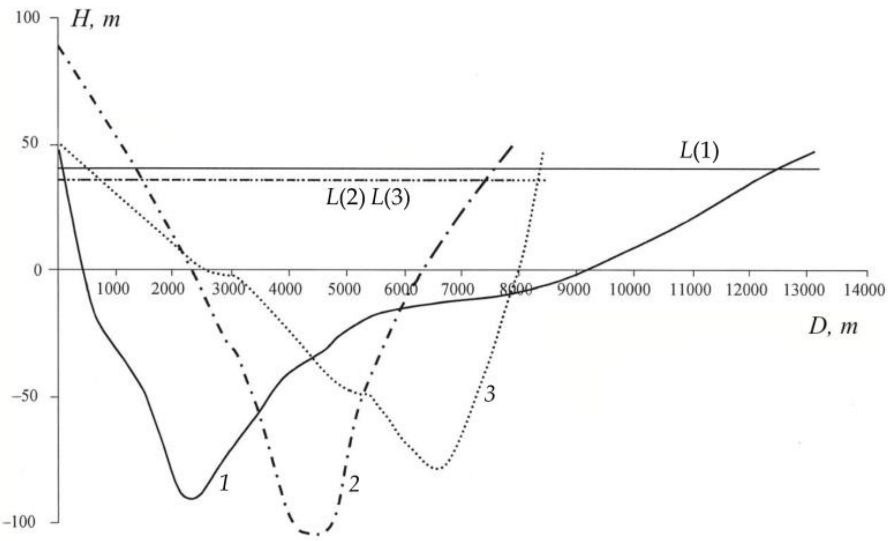

Figure 3. Transverse profiles of the Paleo-Volga River valley and their correlation with the maximum depths of the modern Volga River in different parts of its course. *D*—distance along the profile line, *H*—absolute elevation; the Neogene incisions along the following profiles: *1*—Bol. Klyuchi–Vasilyevo (S1, see Figure 1), *2*—Derzhavino–Kuyuki (S2), *3*—Nizhnyaya Kondratka–Gorka (S3); *L*(1), *L*(2) and *L*(3)—maximum depths of the modern Volga riverbed according to the profiles S1, S2 and S3, respectively.

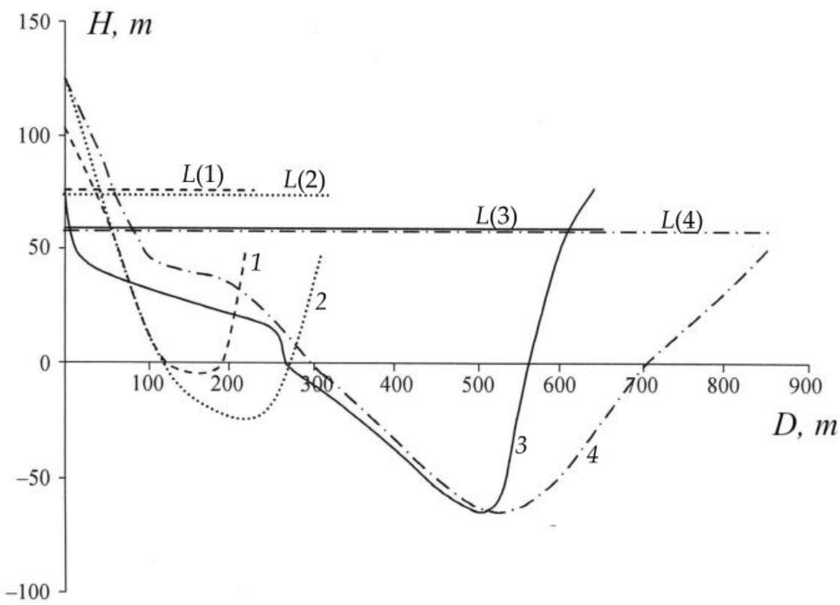

Figure 4. Transverse profiles of the Paleo-Sheshma River valley and their correlation with the maximum depths of the modern Sheshma River in different parts of its course. *D*—distance along the profile line, *H*—absolute elevation; the Neogene incisions along the following profiles: *1*—Verkhnyaya Karmalka–Nizhnyaya Karmalka (S4, see Figure 1), *2*—Cherniy Klyuch–Klementeykino (S5), *3*—Sloboda Cheremukhovaya–Novosheshminsk (S6), *4*—Sloboda Ekaterininskaya–Novosheshminsk (S7); *L*(1), *L*(2), *L*(3) and *L*(4)—maximum depths of the modern Sheshma riverbed according to the profiles S4, S5, S6 and S7, respectively.

Table 1. Morphometric characteristics of the Neogene paleovalleys of the study region.

Paleovalley (Settlement), See Figure 1	*W*(1)	*W*(2)	*I*	*G*	*L*
Paleo-Volga (Derzhavino), S2	4.2/1.2	8.6	−81.0	13/16–18	Dolomites, gypsum, limestones
Paleo-Kama (Kamskie Polyany), S15	1.8/0.8	3.5	−105.0	18/20–21	Dolomites, limestones
Paleo-Sviyaga (Kireyevo), S14	1.4/1.0	3.0	−42.0	14–15/17	Dolomites, clays
Paleo-Sheshma (Sloboda Ekaterininskaya), S7	3.7/0.8	7.5	−63.8	9/13	Dolomites, limestones
Paleo-Zay (Aksarino), S9	2.5/0.6	3.5	−45.0	13/24	Limestones, dolomites, clays
Paleo-Ik (Bolshoy Chekmak), S11	2.3/0.7	12.5	−34.5	13–14/22	Dolomites, limestones

W(1)—the width of pre-Akchagyl incision (km) (top/bottom); *W*(2)—the total width of paleovalleys (km); *I*—erosion incision absolute elevation (m); *G*—paleovalley slope gradient (°) (left/right); *L*—lithological structure of rocks composing the sides of paleovalleys.

The lithology of the rocks composing the sides of the paleovalleys played an important role in their appearance. The steepness of the sides of the pre-Akchagyl valleys cut in clayey rocks did not exceed 5–9°. In carbonate rocks (limestones and dolomites), this value reached 20–26°.

The incision of modern rivers almost throughout the entire territory is located above the Neogene (pre-Akchagyl) incision (Figures 3 and 4). The exception is the areas in the upper reaches of small tributaries of paleorivers. Within various river systems, the features of the elevation ratio of the incision of modern valleys and the Neogene (pre-Akchagyl) incision are significantly different. The maximum value of the vertical displacement of the modern incision relative to the pre-Akchagyl one is noted for the Volga River after the confluence with the Kama River (more than 200 m). The vertical displacements of the incisions for the middle Volga River and lower Kama River before their confluence are no more than 150 m. For the tributaries of the Volga River and Kama River, the largest displacements are observed within their lower reaches. For large tributaries such as the Sviyaga, Sheshma, Zay and Ik rivers, the difference in the elevation position of the bottoms of incisions reaches 100–120 m; for small ones, 70–85 m. In the upper reaches of the rivers, the vertical displacement of incisions decreases to 25–30 m.

It is important to note that the gradients of the bottoms of the Neogene (pre-Akchagyl) paleovalleys exceeded the modern ones by 5–6 times and in some areas even more. On average, the gradients of the Paleo-Kama River within the study area were 0.1–0.2 m/km, while the maximum gradients reached 0.3–0.5 m/km. The gradients of the pre-Akchagyl Volga River valley bottom could reach 0.8–1.0 m/km; in some parts of the valley, they approached even 3.5–5.0 m/km. The gradients of the pre-Akchagyl valley bottoms of the Sulcha, Sheshma, Zay and Ik rivers were 0.7–1.1 m/km; in some areas and closer to the upper reaches, they were 1.0–3.0 m/km [24].

3.2. The History of the Development of the Regional Buried River Valley Network

Buried river valleys of the Neogene and Early Quaternary have gone through a full cycle of development from inception to almost complete conservation (complete filling). According to the data of the modern stratigraphic scale (Table 2), the time interval of this development of the valleys was about 5.0 (or 5.3) million years [28,29].

Table 2. Comparison of Russian and regional stratigraphic scales.

Russian Stratigraphic Scales [28,29]				**Regional Stratigraphic Scales**	
				South of European Russia [29,30]	**Middle Volga Region**
Period	**Epoch**	**Subepoch**	**Stage**	**Regional Stage**	**Layers**
Quaternary	Pleistocene	Early	Gelasian	Gelasian	Biklyan Chistopol (with Akkulaev layers)
Neogene	Pliocene	Late Early	Piacenzian Zanclean	Akchagyl Cimmerian	Sokol Chelny
	Miocene	Late	Messinian	Pontian	Sheshma

Over such a long period in the river valleys, the systems of erosion and sedimentation repeatedly changed. The analysis of geological profiles and, first of all, transverse geological sections of paleovalleys, made it possible to trace the change in the conditions of sedimentation in river valleys according to the change in lithological differences. The main stages of their development are taken to be the largest time intervals corresponding to the time of incision and the subsequent change in the types of sediment accumulation. As mentioned above, only buried valleys are considered, the development of which began in the Neogene.

3.2.1. Neogene

The time of incision of river paleovalleys is considered differently by various authors. Goretsky [16], Kirsanov [17] and Obedientova [18] attributed the incision of paleovalleys and the formation of the lower Sheshma layers (horizons) to the Middle Pliocene. A different point of view was expressed by Rozhdestvensky [31] and Yakhimovich [32], who believed that the incision of river valleys occurred in the Late Miocene or Early Pliocene. The latest data on the stratigraphy of the Neogene and Quaternary deposits suggest many paleovalleys in this region date to the Late Miocene age (see Table 2).

The incision of river valleys, according to modern dating of the stratigraphic scale, began in the Late Miocene (Pontus). The river network originated against the background of climatic and tectonic rearrangements of the entire east of the Russian Plain and the Caspian Sea. The uplift of the Urals and the eastern edge of the Russian Platform in the Late Miocene resulted in the activation of various tectonic structures that played a significant role in the formation of the future extensive hydro-network [33]. Ascending movements were experienced by the Northern and Southern Tatar tectonic arches of the platform, the negative structures were finally formed—the Melekes Depression and the Zavolzhsky Trough, which later played a significant role in the formation of the region's hydro-network [34]. Almost simultaneously with the uplift of the east of the Russian Platform, the Caspian Syneclise subsided and the depression of the South Caspian was transformed [35].

The so-called Messinian ecological crisis, which occurred in the Late Miocene in the Mediterranean, was also reflected in the Black Sea–Caspian Sea megaregion [36]. The aridization of the climate resulted in the drying up of vast areas of this region. The Caspian Sea, having lost its connection with the Black Sea paleowaterbody, continued to exist in the form of isolated water objects. Most likely, the deep-water regime then persisted only in the South Caspian Depression, while its level dropped to −500–600 m. The presence of the Neogene paleovalley of the Volga River at close levels indicates its formation during the period of a sharp drop in the level of the Caspian Sea [37].

In the Middle Volga region, in the Late Miocene, on the contrary, moderately warm and humid climatic conditions prevailed [16,38,39]. Significant moistening of the territory and increasing elevation differences contributed to intense deep erosion and the development of ultra-deep valley incisions of the Paleo-Kama (Paleo-Belaya), Paleo-Volga and their tributaries. As we said before, the maximum recorded incision depth of the Paleo-Volga was −201.4 m below sea level. The change in the level of the Caspian Sea further determined the development of the study territory's paleovalleys. The role of other factors throughout the history of the development of paleovalleys in the Neogene–Early Quaternary time was not so noticeable (Figure 5).

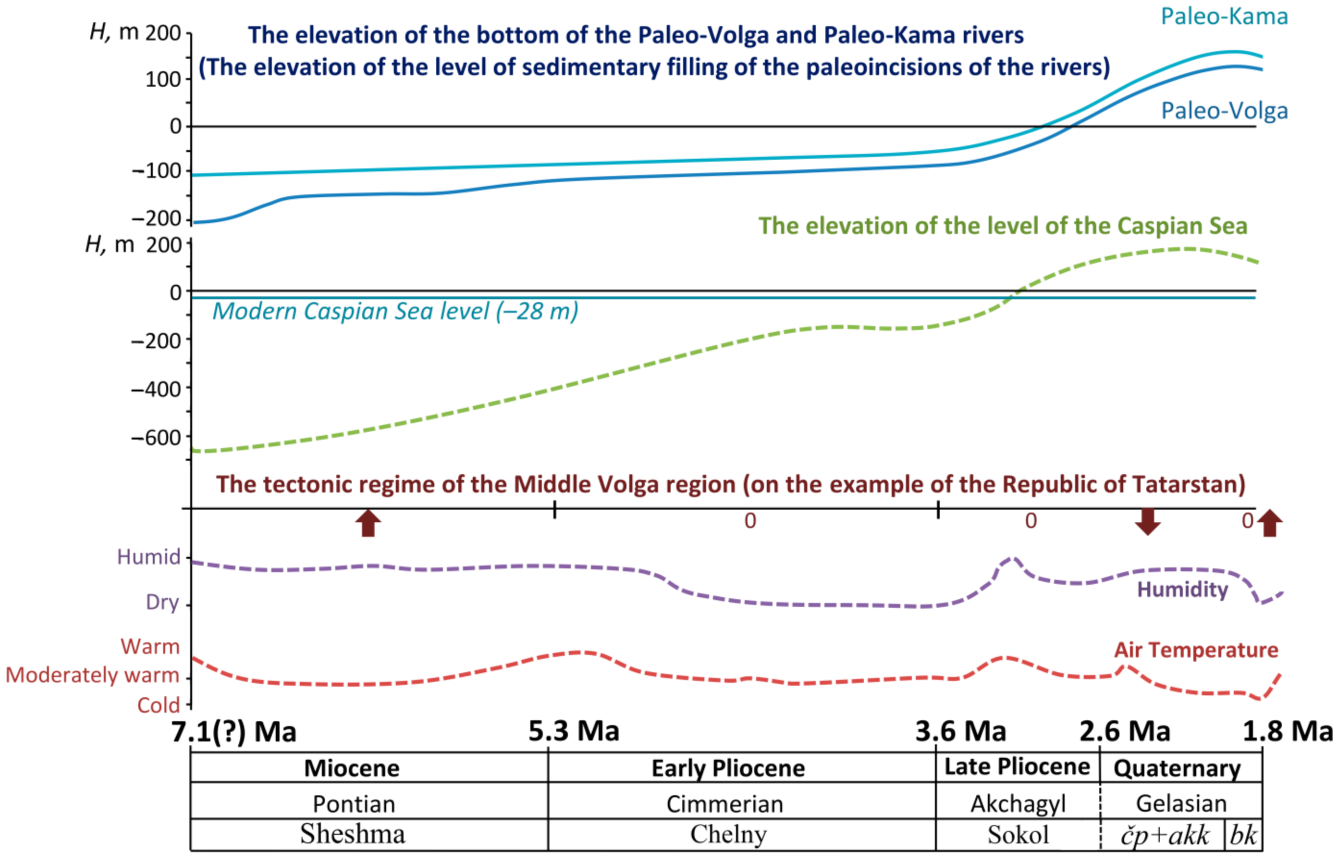

Figure 5. Changes in the elevation of the bottom of the middle Paleo-Volga (at Chuvash Burnaevo, see Figure 1) and lower Paleo-Kama (at Mal. Tolkish, see Figure 1) rivers and factors controlling them in the Neogene and Early Quaternary (based on the data from [16,19,27,34,35,37–39]). *H*—absolute elevation; solid curved line—according to geological well data; dotted curved line—according to published literature data; *čp*—Chistopol layers, *akk*—Akkulaev layers; *bk*—Biklyan layers. The dotted line in the table is the assumed time boundary.

In the Pontus, the filling of erosion incisions with alluvial deposits (the Sheshma layers) began. The Sheshma layers are deposits, including washout facies and channel facies, confined to the deepest parts of paleovalleys [16]. They are represented in studied geological profiles by detritus, gravel–pebble deposits, sands and sandy clays. The composition of the gravel–pebble material is dominated by rounded or weakly rounded local rocks (sandstones, limestones and dolomites). Quartz sands are predominantly fine-grained, less often inequigranular, often silty and silty-argillaceous. The clays are brown, brownish-gray and often sandy. The thickness of the deposits varies from 5–10 to 40 m. Linkina [38] identified three complexes in the Sheshma deposits: broad-leaved-birch, broad-leaved-pine-spruce and spruce. In paleomagnetic terms, the Sheshma layers are poorly studied, have a positive magnetization and are conditionally assigned to the Chron C3A. However, this issue requires further study. The presence of the Sheshma deposits in the valleys of the Belaya/Kama River, Volga River and their large tributaries—the Sheshma, Zay, Ik, Vyatka and Sviyaga rivers—as well as smaller tributaries, allows for it to be concluded that the basis of the pattern of the study territory's hydro-network was laid already in the Late Miocene (Pontian time).

The rise in the level of the Caspian Sea in the Early Pliocene (Cimmerian time) resulted in the flooding of the river valleys of the Middle Volga region and the "damming" of the river runoff. Under conditions of regulated runoff, a special type of waterbody ("river-lake") was formed with a very slow flow and low eroding capacity. Moderately cool and fairly humid climatic conditions established at that time in the territory determined a significant amount of precipitation [16,38,39]. Alluvial sedimentation in river valleys changed to lacustrine–alluvial (the Chelny layers). The Chelny layers lie in the deepest parts of the Neogene valleys (Figure 6). The thickness of these deposits ranges from 5 to 76 m. The absolute elevations of the base of this formation vary from 4.5 m (in the upper reaches of the valleys) to −144.4 m. The deposits are represented by gray, dark gray and, less often, brown clays, interbedded with silt and sand. In contrast to the underlying Sheshma deposits, the Chelny clays are characterized by thin horizontal and ribbon bedding and a more uniform lithological composition. This indicates the predominance of the lacustrine type of sediment accumulation in the river valleys. In the geological sections of the Paleo-Kama River valley, clays make up more than 60% of the composition; sands, silts and gravel–pebble materials account for less than 40%.

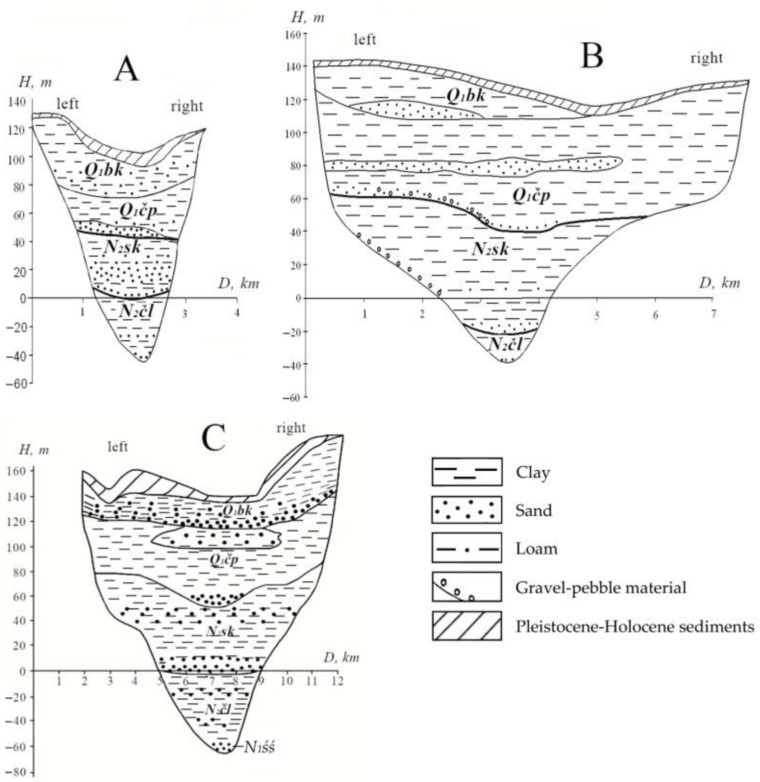

Figure 6. Transverse profiles of the Paleo-Zay (**A**) (S9, see Figure 1), Paleo-Ik (**B**) (S11) and Paleo-Sheshma (**C**) (S7) river valleys. Q_1bk—Early Quaternary sediments: Biklyan layers; $Q_1\check{c}p$—Early Quaternary sediments: Chistopol layers; N_2sk—Neogene (Late Pliocene) sediments: Sokol layers; $N_2\check{c}l$—Neogene (Early Pliocene) sediments: Chelny layers; $N_1\acute{s}\acute{s}$—Neogene (Late Miocene) sediments: Sheshma layers. *D*—horizontal distance; *H*—absolute elevation.

In the middle Volga River paleovalley, the Chelny deposits are more sandy. The sands are gray, brownish-gray, quartz fine- and medium-grained. The clays are gray and sandy with siltstone interbeds. The spore–pollen complexes are dominated by coniferous representatives of the genera Picea, Pinus and Abies [39]. According to the paleomagnetic scale, the Chelny deposits correspond to the Chron Gilbert with reversed magnetization.

In the valley of the Paleo-Kama River and the lower reaches of its large tributaries, in the valley of the Paleo-Volga River (after flowing into the Paleo-Kama River), the lacustrine–river type of sedimentation prevailed during the entire Cimmerian time. On the contrary, in the valley of the Paleo-Volga River up to the city of Kazan and its large tributary Paleo-Sviyaga River and in the valleys of the upper reaches of small tributaries of the Paleo-Kama River, river sedimentation processes prevailed. The sections contain a fairly large proportion of sandy fractions; in addition, breakstone material occurs in the lower parts of the sections.

At the turn of the Early and Late Pliocene, the level of the Caspian Sea stabilized (see Figure 5). The climatic conditions in the Middle Volga region in the Late Pliocene were generally moderately warm and moderately humid with an annual precipitation of at least 600 mm [38,39]. This resulted in an increase in runoff in the river valleys and activation of erosion processes in river channels. In the river valleys, the formation of alluvial deposits (the Sokol layers) began.

At present, the two systems include a single complex of sediments that composes the upper parts of the paleovalleys, which previously belonged to the Akchagyl complex of the Pliocene. According to the regional scale of the Neogene, only the Sokol layers (currently it is the Akchagyl regional stage) are conditionally assigned to the Late (Upper) Pliocene. The overlying layers (the Chistopol and Biklyan layers) conventionally belong to the Pleistocene. This issue requires further study. Within the study area, the Sokol deposits almost everywhere lie with washout on the deposits of the Early Pliocene, except for some upper reaches of the paleorivers, where they cut into the bedrock of the Permian. This suggests that the Sokol (Akchagyl) incision did not exceed the Late Miocene one in size. The lower part of the Sokol layers is composed of typically alluvial deposits. The Sokol deposits are represented by a thick layer of sands, sandstones, clays and silts. In the lower reaches of the paleorivers, as well as on the side parts of the valleys, the Sokol deposits are more clayey. In a number of geological sections of the Sokol deposits, two rhythms of sedimentation are distinguished—from sands at the base to clays at the top. At the base of the first rhythm, as a rule, there are sands, often with gravel–pebble material, from local rocks; higher up they are replaced by clays and silts. The thickness of the deposits is from 12.0 to 93.0 m. The absolute elevations of the sole are from -39.5 to +60.7 m. The spore–pollen spectra of the Sokol time are characterized by the dominance of pollen from coniferous tree species Picea and Pinus with a large proportion of broad-leaved species. The pollen of Tilia, Ulmus, Carpinus, Fagus and Quercus are relatively abundant [16,38,39]. According to paleomagnetic data, the Sokol deposits are directly magnetized and correspond to the Chron Gauss (3.59–2.59 Ma). The time boundary between the Sokol and Chistopol deposits coincides with the time boundary between the Chron Gauss and Chron Matuyama ($\approx$2.6 Ma).

In the Late Pliocene, against the general background of the development of ingression, the level of the Caspian (Akchagyl) paleowaterbody underwent some fluctuations, which were reflected in the features of sedimentation in river valleys, where the alluvial type of sedimentation was replaced by a lacustrine–alluvial one. The rhythmicity of sedimentation is most clearly seen in the lower Paleo-Kama River valley and the lower reaches of its right tributaries. In the middle Paleo-Volga River valley, the deposits of the Sokol layers are more sandy, especially in the axial part of the paleovalley, which may indicate good flowability through the Sokol time.

The advance of the Caspian Sea waters at the turn of the Pliocene and Pleistocene resulted in the formation of a stagnant estuary (firth?) within the lower Kama River valley. The proximity of the sea is indicated by the appearance of freshwater–brackishwater representatives of ostracods of the species *Leptocythere nalivkini* Step., *Caspiollina maschricovi* Ros. in these paleowaterbodies [19]. The predominant type of sedimentation in the studied river valleys of that time was lacustrine–alluvial and lacustrine–estuarine.

3.2.2. Early Quaternary

In the Early Pleistocene (Gelasian Stage), the development of the river network of the Middle Volga region took place against the backdrop of the most significant transgression of the Caspian Sea (previously, the maximum phase of the Akchagyl Transgression). The subsidence of the Melekes Depression and the Sarailin Trough contributed to the movement of water along the Paleo-Volga/Kama valley and further along the Paleo-Kama River valley up to the confluence with the Paleo-Belaya River [19]. The ingression of the Caspian Sea waters has left its mark on climate change. This resulted in even greater cooling and moistening of the Middle Volga region [38,39].

At the turn of the Neogene and Quaternary, in the river valleys of the Middle Volga region, the Chistopol layers (together with the Akkulaev layers) formed, which, without erosion or with a weak break, laid down on the Sokol layers. They are mainly represented by clays, sands and silts. Clays are dark gray, gray, brownish-gray and brown with thin layers of gray silts. The sandiness of the deposits increases in the axial parts of the paleovalleys, primarily in the Paleo-Volga River valley. The sands in the Paleo-Kama River geological sections are mostly gray, bluish-gray, weakly calcareous and medium-fine-grained, at the base of the sections often with gravel and pebbles of various roundness. The absolute elevations of the sole are from 20 to 100 m. The thickness of the deposits varies from 6 to 95 m. The Chistopol deposits are characterized by a variety of palynoassemblages with a predominance of Picea and Pinus [38,39]. According to paleomagnetic data, the Chistopol deposits are correlated with the beginning of the Chron Matuyama and are characterized by the reverse magnetization of the beginning of the Subchron Reunion.

In the Chistopol time, the river network was a kind of regulated lake–river system, first flooded and then almost completely occupied by sea waters. The level of this waterbody was found at 160–180 m a.s.l. This is a thick layer of lacustrine–alluvial and lagoon–marine deposits. The variety of hydrodynamic conditions within the waterbody has resulted in different types of sedimentation. Freshwater lacustrine–alluvial deposits formed in the dammed river valleys at the initial stages of flooding.

As sea waters entered, freshwater sediments were overlapped in the lower Kama River paleovalley by brackishwater lacustrine sediment and then by lagoon–marine sediment with typical representatives of marine fauna (*Cerastoderma C. dombra dombra* (Andrus.), *C. pseudoedule* (Andrus.), *Avimactra subcaspia* (Andrus.), etc.), which indicates marine and lagoonal marine type of sedimentation [16,19]. The greatest thicknesses and the most complete geological sections of the Chistopol deposits are confined to the lower Kama River paleovalley, as well as to the lower reaches of the Ik, Sheshma and Zay river valleys. In areas adjacent to the paleovalleys, coastal and lagoon–marine deposits (the Akkulaev layers) were formed.

The lacustrine–alluvial type of sedimentation throughout the entire time was preserved only in paleorivers flowing within the Bugulma–Belebey Upland and the Volga Upland. Upstream from the city of Kazan, sediments with marine fauna were not recorded. This indicates the existence of a retaining lake–river waterbody in the Paleo-Volga River valley during this period. In the axial parts of the paleovalleys of the middle Volga River (upstream of the city of Kazan, see Figure 1) and Sviyaga River, the Chistopol deposits are represented mainly by sandy and sandy-argillaceous deposits, in the lower part with the inclusion of gravel–pebble material, which indicates the flow of these rivers during the period of maximum transgression.

By the end of the Gelasian time (Early Pleistocene), the area occupied by the Caspian Sea began to reduce. This was facilitated both by the changed tectonic and climatic conditions in the region of the modern Caspian Sea and by the more arid conditions established within the Middle Volga region. In the studied paleovalleys, a change in sedimentation took place, which resulted in the formation of the Biklyan deposits.

The Biklyan layers are traced along the studied geological sections above the Chistopol layers. Most of the sections, especially on the lower Kama River, are composed of dark gray, gray-brown clays, thinly bedded with silt interbeds. The lower parts of the sections are sandy; there are yellowish-brown, gray, fine-grained, quartz sands, at the base with an admixture of gravel–pebble material of carbonate rocks. In the valleys of the Volga and Sviyaga rivers, the Biklyan deposits are partially eroded and occur in separate fields. The absolute elevation of their sole ranges from 72 to 181.4 m. The thickness of the deposits varies from 3 m in the upper reaches of the marginal parts of paleovalleys to 68 m in the lower reaches of large paleovalleys. The Biklyan deposits are characterized by the predominance of herbaceous plants in the total composition of pollen (up to 60–70%), mainly Chenopodioídeae and Artemísia. Among the trees, pollen of birch and pine are recorded [16,38]. In paleomagnetic terms, the Biklyan deposits are characterized by the reverse magnetization of the Chron Matuyama from the beginning of the Subchron Reunion with direct magnetization to the beginning of the Subchron Olduvai.

In the Biklyan time, the lowering of the erosion base caused a new incision in the river valleys and above all in the valleys of the tributaries of the Paleo-Kama River. In the Paleo-Kama valley, the Biklyan deposits are in the marginal parts of the valley. The lower part of the Biklyan layers is composed of sands, with an admixture of clays, crushed stone and pebbles of Permian rocks. In the upper reaches of the paleovalleys of the left tributaries of the Paleo-Kama River, the Biklyan pebbles and sands are located on the eroded surface of the Permian deposits. At the base, the deposits are represented by sands with small pebbles; in the Sviyaga River valley, often by pebbles. Thus, at the very beginning of the Biklyan time, erosion processes in river valleys (vertical and horizontal channel deformations) prevailed over accumulative ones. The intensive activity of rivers contributed to the desalination of residual waterbodies. This resulted in a reduction in the faunal composition of marine and brackishwater representatives and an increase in the proportion of freshwater ones [16]. In the valleys of the large Paleo-Kama and Paleo-Volga rivers, primarily in the central parts of their paleovalleys, the lagoon–marine type of sedimentation changed to lacustrine–alluvial and alluvial ones. In the bays and marginal parts of the regressing waterbody, as well as in the residual waterbodies preserved in natural depressions, weakly brackish coastal–lagoonal and freshwater lacustrine–alluvial deposits were formed.

Increasing aridization of the climate, associated with the retreat of the waters of the Akchagyl paleowaterbody to the south [16,38], against the background of the tectonic stability of the territory, resulted in a change in erosion and erosion–sedimentation processes in river valleys to sedimentation ones. Over time, sedimentation in the river valleys became predominant. In all paleovalleys, alluvial pebbles and sands were replaced by clayey lacustrine-alluvial deposits up the geological sections. Intensive sedimentation contributed to the filling of the upper parts of paleovalleys and low interfluvial areas with these deposits up to 140–160 m a.s.l. In the upper reaches of tributary rivers, the sedimentation level reached 180–200 m a.s.l.

By the end of the Gelasian Stage, the area of the Volga-Kama paleowaterbody decreased significantly. On the vast expanses previously occupied by vast river valleys, low-lying surfaces (accumulative lowlands) began to form. In the residual waterbodies in the Paleo-Kama River valley, lacustrine–alluvial deposits were formed, which were called "Omar deposits" [16]. These deposits occur at absolute elevations of 120–180 m. Their temporal dating (the Gelasian–Calabrian (?) time boundary), as well as their relationship with the Biklyan layers in sections, requires further study.

The development of the river network in the Middle Volga region in the Neogene and Early Quaternary took place under the intense influence of the Caspian Sea (Figure 5). It was this factor that influenced the morphological and morphometric characteristics of paleovalleys and their development. The origin of river valleys took place during the period of maximum regression of the Caspian Sea, while the development of the network of valleys occurred during its growing ingression. The maximum phase of ingression (formerly the Akchagyl Transgression) within the study area, according to modern dating of stratigraphic scales, falls on the Early Quaternary. If in the Pliocene the river network was a regulated river system, then in the Early Quaternary it was partially flooded by sea waters. This determined the peculiarity of sedimentation in the river valleys. The predominant type of sedimentation in the river valleys of the Pliocene was lacustrine–alluvial; in the Early Quaternary, there was a change from lacustrine–alluvial to lagoonal–marine type and then, as the Caspian paleowaterbody regressed, to lacustrine–alluvial and lacustrine types. By the end of the Gelasian Stage, this was the main type of sedimentation in the river valleys. In the Pleistocene, at the turn of the Gelasian and Calabrian stages, a major cycle of valley formation was completed, which began as early as the Neogene.

3.3. Limitations

A number of issues remain open during the study. The issues of stratigraphy, on which the history of the development of the region's paleovalleys is based, turned out to be unresolved. Clarifications require such issues as the age dating of the Miocene deposits (the Sheshma deposits) in the middle Volga River paleovalley (the Pontian Stage), the ratio (in the geological sections) of the regional Sheshma and Chelny layers of the Paleo-Volga valley, the "volume" of the regional Akchagyl stage in the regional scheme and its synchronization with the stratigraphic scale of the southeast of the Russian Plain and the position of the Biklyan and Omar deposits in the Pleistocene regional scheme.

4. Conclusions

The general pattern of the position of the paleovalleys of the Neogene and Early Quaternary of the Middle Volga region is close to the modern configuration. The largest rivers of the study period were the Paleo-Kama (Belaya) River and Paleo-Volga River. At present, the studied paleovalleys are located mainly to the left of the modern river incisions. Thus, right-hand displacement of rivers was predominant in the Quaternary. The magnitude of the displacement of the paleovalleys directly depended on the size of rivers. The ratio of the depths of the modern and Neogene incisions was determined by the position of the Caspian Sea level. The same factor mainly determined the morphometric parameters of paleorivers and also influenced the morphological appearance of paleovalleys. Based on the analysis of transverse geological profiles and reference geological wells in the study region, it was possible to trace the history of the development of paleovalleys in the Neogene–Early Quaternary time, according to modern data on the stratigraphy of the region.

Features of sedimentation in river valleys, as well as, in general, the development of the river valley network in the Neogene and Early Quaternary were determined mainly by fluctuations in the level of the Caspian Sea. The formation of river valleys began during the period of maximum regression of the Caspian paleowaterbody, while the development of the valley network took place during the period of increasing ingression. If in the Miocene and Pliocene, the lacustrine–alluvial type of sedimentation prevailed in the river valleys, then in the Early Quaternary (Gelasian Stage), against the background of maximum ingression, it changed to the lagoonal–marine type and then, at the end of this time, to the lacustrine–alluvial type as the waters of the Caspian Sea receded. The alluvial type of sedimentation persisted only within the upper reaches of the tributaries of large rivers. The filling of paleovalleys with sediments ended at the Gelasian–Calabrian time boundary. Thus, a long stage of river valley formation in the study region was completed.

The study of the buried valleys of the region using GIS technologies allows us to propose the used research methodology for other areas of the east of the Russian Plain. This contributes to the study of the paleogeography of not only this region but also the Caspian Sea, which is closely historically associated with it, as the largest body of water on the planet, which currently does not have a runoff into the world ocean.

Author Contributions: Conceptualization, E.V.P.; methodology, E.V.P.; software, E.V.P. and A.V.G.; validation, E.V.P. and A.V.G.; formal analysis, E.V.P.; investigation, E.V.P.; resources, E.V.P.; data curation, E.V.P. and A.V.G.; writing—original draft preparation, E.V.P., A.V.G. and A.A.B.; writing—review and editing, E.V.P., A.V.G. and A.A.B.; visualization, E.V.P. and A.V.G.; supervision, A.V.G.; project administration, E.V.P.; funding acquisition, A.V.G. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the Kazan Federal University Strategic Academic Leadership Program (PRIORITY-2030) and the subsidy allocated to Kazan Federal University for the state assignment project NO FZSM-2023-0023 in the sphere of scientific activities.

Data Availability Statement: Not applicable.

Acknowledgments: The authors are grateful to V.V. Mozzherin, Kazan Federal University, for consultations on the method of reconstruction of paleovalleys.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Galitsky, V.I. *Fundamentals of Paleogeomorphology*; Nauk. Dumka: Kyiv, Ukraine, 1979. (In Russian)
2. Nikitin, S.I. General Geological Map of Russia. 57th sheet. *Proc. Geol. Comm.* **1890**, *5*, 321. (In Russian)
3. Thomas, C.R. Flank production of the Nemaha Mountain, Kansas. In *Structure of Typical American Oil Fields*; American Association of Petroleum Geologists: London, UK, 1929; Volume 1, pp. 60–724.
4. Bridge, J. *Geology of the Eminence and Cardareva Quadrangles, Ser. 2nd*; Missouri Bureau of Geology and Mines: Rolla, MO, USA, 1930; 23p.
5. Mirtova, A.V. Pliocene. In *Geology of the Tatar Autonomous Soviet Socialist Republic and Adjacent Territories within 109 Sheets Part 3*; State United Scientific and Technical Publishing House: Moscow-Lenigrad, Russia, 1939; pp. 221–228. (In Russian)
6. Eichwald, I.S. *Geognosy Predominantly in Relation to Russia*; Printing House of K. Wingeber: St. Petersburg, Russia, 1846; 572p. (In Russian)
7. Golovkinsky, N.A. On post-tertiary formations along the Volga in its middle course. *Sci. Notes Kazan Univ.* **1865**, *1*, 451–524. (In Russian)
8. Shtukenberg, A.A. The northern boundary of the Caspian Sea in the post-Pliocene period. *Append. Protoc. Nat. Soc. Kazan Univ.* **1885**, *81*, 4. (In Russian)
9. Krotov, P.I.; Nechaev, A.V. Kazanskoye Zakamye in Geological Relation. *Proc. Nat. Soc. Kazan Univ.* **1890**, *22*, 318. (In Russian)
10. Rosen, F.F. About question of the nature of post-tertiary formations along the Volga River. *Proc. Nat. Soc.* **1879**, *8*, 45. (In Russian)
11. Nikitin, S.N. Excursion to the region of the rivers Sok, Kinel and some following Volga areas. *News Geol. Comm. Russ.* **1886**, *5*, 239–262. (In Russian)
12. Andrusov, N.I. *Selected Works*; Publishing House of the Academy of Sciences of the USSR: Moscow, Russia, 1961; Volume 1, 712p. (In Russian)
13. Pavlov, A.P. Neogene and post-Tertiary deposits of Southern and Eastern Europe. Comparative stratigraphy of freshwater deposits. In *Memoirs of the Geological Society Department of Amateurs of Natural Science, Anthropology and Ethnography*; Moscow, Russia, 1925. Available online: http://gpntb.dlibrary.org/ru/nodes/3205-pavlov-a-p-memuary-geologicheskogo-otdeleniya-obschestva-lyubiteley-estestvoznaniya-antropologii-i-etnografii-vyp-5-neogenovye-i-posletretichnye-otlozheniya-yuzhnoy-i-vostochnoy-evropy-sravnitelnaya-stratigrafiya-presnovodnyh-otlozheniy-m-1925 (accessed on 15 April 2023).
14. Mazarovich, A.N. Stratigraphy of the Quaternary deposits of the Middle Volga. In Proceedings of the Commission for the Study of the Quaternary Period; Publishing House of the Academy of Sciences of the USSR: Moscow-Leningrad, Russia, 1935; Volume 4, pp. 91–118. (In Russian).
15. Tikhvinskaya, E.I. About the ancient erosion in the valley zone of the Volga near Kazan. *Sci. Notes Kazan Univ.* **1954**, *114*, 165–170. (In Russian)
16. Goretsky, G.I. *Alluvium of the Great Anthropogenic Ancient Rivers of the Russian Plain*; Nauka: Moscow, Russia, 1964; pp. 1–415. (In Russian)
17. Kirsanov, N.V. Akchagyl of the Volga region. In *Stratigraphy of the Neogene of the East of the European Part of the USSR*; Nedra: Moscow, Russia, 1971; pp. 22–45. (In Russian)
18. Obedientova, G.V. *Erosion Cycles and the Formation the Volga River Valley*; Nedra: Moscow, Russia, 1977. (In Russian)
19. Sidnev, A.V. *History of Hydrographic Pliocene Network Development in the Sub-Ural Region*; Nauka: Moscow, Russia, 1985; pp. 1–220. (In Russian)
20. Kuznetsov, S.S. Cenozoic paleovalleys of the Volga-Kama interfluve. In *Age and Genesis of Overdeepening on the Shelves and the History of River Valleys*; Nauka: Moscow, Russia, 1984; pp. 110–118. (In Russian)
21. *Morphostructure and Morphosculpture of the Platform Plains of the USSR and the Bottom of the Surrounding Seas*; Gerasimov, I.P., Aseyev, A.A., Eds.; Academy of Sciences of the USSR, Institute of Geography; Nauka: Moscow, Russia, 1986; pp. 53–62.
22. Dedkov, A.P. The upper plateau of the East European Plain. *Geomorfologiya* **1993**, *4*, 82–89. (In Russian)
23. Dedkov, A.P.; Mozzherin, V.V. Eopleistocene. Geology of Tatarstan. In *Stratigraphy and Tectonics*; Geos: Moscow, Russia, 2003; pp. 242–248. (In Russian)
24. Petrova, E.V. The patterns of Neogene river valley distribution within the territory of the Republic of Tatarstan and its relation to modern river network. Scientific Notes of Kazan University. *Ser. Geol. Sci.* **2008**, *150*, 43–50. (In Russian)
25. Cressie, N.A. The Origins of Kriging. *Math. Geol.* **1990**, *22*, 239–252. [CrossRef]
26. State Geological Map of the Russian Federation. *Scale 1:1,000,000. (New Series). Sheet Number—(38), 39—Samara. Explanatory Note*; VSEGEI: St. Petersburg, Russia, 2000; 325p. (In Russian)

27. Popov, S.V.; Antipov, M.P.; Zastrozhnov, A.S.; Kurina, E.E.; Pinchuk, T.N. Sea level fluctuations on the northern shelf of the Eastern Paratethys in the Oligocene–Neogene. *Stratigr. Geol. Correl.* **2010**, *18*, 99–124. (In Russian) [CrossRef]
28. *Stratigraphic Codex of Russia. Third edition, corrected and enlarged*; Zhamoida, A.I., Ed.; VSEGEI: St. Petersburg, Russia, 2019; 96p. (In Russian)
29. Gladenkov, Y.B. Neogene. In *General Stratigraphic Scale of Russia: Current Status and Trends of Development*; Geological Institute of the Russian Academy of Science: Moscow, Russia, 2013; pp. 341–350. (In Russian)
30. Nevesskaya, L.A.; Kovalenko, E.I.; Beluzhenko, E.V.; Popov, S.V.; Goncharova, I.A.; Danukalova, G.A.; Zhidovinov, N.Y.; Zaitsev, A.V.; Zastrozhnov, A.S.; Pinchuk, T.N.; et al. Regional stratigraphic scheme of the Neogene in the south of the European part of Russia. *Otechestvennaya Geol.* **2005**, *4*, 47–59. (In Russian)
31. Rozhdestvensky, A.P. *The Latest Tectonics and Development of the Relief of the Southern Urals*; Nauka: Moscow, Russia, 1971; p. 302. (In Russian)
32. Yakhimovich, V.L. Stages of geological development of the Bashkir Cis-Urals in the Neogene. In *Stratigraphy of the Neogene of the East of the European Part of the USSR*; Nedra: Moscow, Russia, 1971; pp. 45–64. (In Russian)
33. Turikeshev, G.T.; Danukalova, G.A.; Kutushev, S.I. *Southern Cis-Urals: Geography, Geology, Tectonics and Geomorphology*; Publishing House "Infra-M": Moscow, Russia, 2016. (In Russian)
34. Voitovich, E.D. Sedimentary cover tectonics. In *Geology of Tatarstan. Stratigraphy and Tectonics*; GEOS: Moscow, Russia, 2003; pp. 313–336. (In Russian)
35. Svitoch, A.A. *Big Caspian: Structure and History of Development*; Publishing House of Moscow University: Moscow, Russia, 2014. (In Russian)
36. *Changes in Climate and Landscapes over the Past 65 Million Years (Cenozoic: From the Paleocene to the Holocene)*; Velichko, A.A., Ed.; GEOS: Moscow, Russia, 1999. (In Russian)
37. Zhidovinov, N.Y.; Kurlaev, V.I. Pliocene deposits of the Northern Caspian. In *Stratigraphy of the Neogene of the East of the European Part of the USSR*; Nedra: Moscow, Russia, 1971; pp. 169–179. (In Russian)
38. Linkina, L.I. Changes in vegetation and climate in the central part of the Middle Volga region in the Neogene (according to spore-pollen analysis). *Sci. Notes Kazan Univ.* **2006**, *148*, 150–161. (In Russian)
39. Bludorova, E.A.; Nikolaeva, K.V. *Geological and Palynological Characteristics of the Pliocene Deposits Near Kazan in Volga and Kama Regions*; Kazan University Publishing House: Kazan, Russia, 1986. (In Russian)