Key Late Cenozoic fluvial archives of eastern Europe: the Dniester, Dnieper, Don and Volga

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MATOSHKO, A.V., GOZHIK, P.F. & DANUKALOVA, G. 2004. Key Late Cenozoic fluvial archives of Eastern Europe: the Dniester, Dnieper, Don and Volga. *Proceedings of the Geologists' Association*, **115**, 141–173. This paper reviews the occurrence, structure, stratigraphy and development of the principal deposits of the Rivers Dniester, Dnieper, Don and Volga. Such archives occur as alluvial accumulations (infills, 'sheets' and fans/deltas), sometimes filling great buried incisions and giving rise, in the modern relief, to plains, valleys and terraces. These accumulations consist of alluvial suites, each with unique lithofacies characteristics. Correlation is based on marker beds from marine transgressions, waste mantles and glaciations, together with mammalian and molluscan biostratigraphy from the fluvial deposits themselves. Overprinted onto a background of predominant incision (typically 160–200 m), within the middle reaches of Dnieper, Don and Volga there are two complete major erosion/aggradation cycles between the Miocene and the late Middle Pleistocene, followed by a younger erosion phase that continues to the present. In contrast, within the Middle Dniester, one such cycle is recorded in the Late Miocene–Early Pliocene, followed by 250–270 m of incision. Most valleys served as arterial channels for intracontinental sediment transport but, where they coincide with ancient rift zones, they represent basins of alluvial accumulation. Neotectonic movements, the dynamics of which have differed between the East European Platform and the transitional zone between this platform and the Carpathian Orogenic Belt, probably controlled the general incision and erosion/aggradation cycles. Climatic oscillations, however, have influenced the structure and composition of the alluvial suites.

Key words: fluvial deposits, Quaternary, Pleistocene, Pliocene, Miocene

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1. INTRODUCTION

The structure and characteristics of the largest fluvial formations (alluvial accumulations, palaeo-incisions and valleys) of the Volga, Don, Dnieper and Dniester river systems (Fig. 1; Tables 1 and 2) are reviewed. The development of these river systems and their precursors can be traced from the Middle Miocene onwards. The first three systems developed under the tectonic regime of the East European Platform, whereas the Dniester system formed the transition zone between this platform and the Carpathian Orogenic Belt. Pleistocene glaciations encroached from the north to cover parts of these fluvial basins, and marine transgressions from the south periodically flooded their lower reaches. Fluvial processes were influenced by Pleistocene climatic oscillations and other factors, all of which are reflected in the structure of fluvial strata and fluvial relief.

The modern Black and Caspian Seas are remnants of the much larger Paratethys Sea, which extended from the Alps to central Asia and became isolated from the global marine environment in the late Middle Miocene (*c.* 13 Ma), at the start of the Sarmatian stage of the regional stratigraphy (e.g. Rögl & Daxner-Höck, 1996; Steininger *et al.*, 1996; Mitchell & Westaway, 1999). In this region reference is made to this local terminology (Fig. 2), since a lack of true marine deposits prevents direct correlation with standard global stratigraphic stages defined by marine biostratigraphy. Subsequent designated stages for the Miocene, Pliocene and Early Pleistocene include: the Meotian (*c.* 10.7–7.1 Ma), equivalent to the Middle–Late Tortonian; the Pontian (*c.* 7.1–5.3 Ma), equivalent to the Messinian; the Kimmerian (*c.* 5.3–3.6 Ma), equivalent to the Dacian or Zanclean (the Early Pliocene); the Akchagyl (*c.* 3.6–1.8 Ma), equivalent to the Piacenzian and Gelasian (the Middle–Late

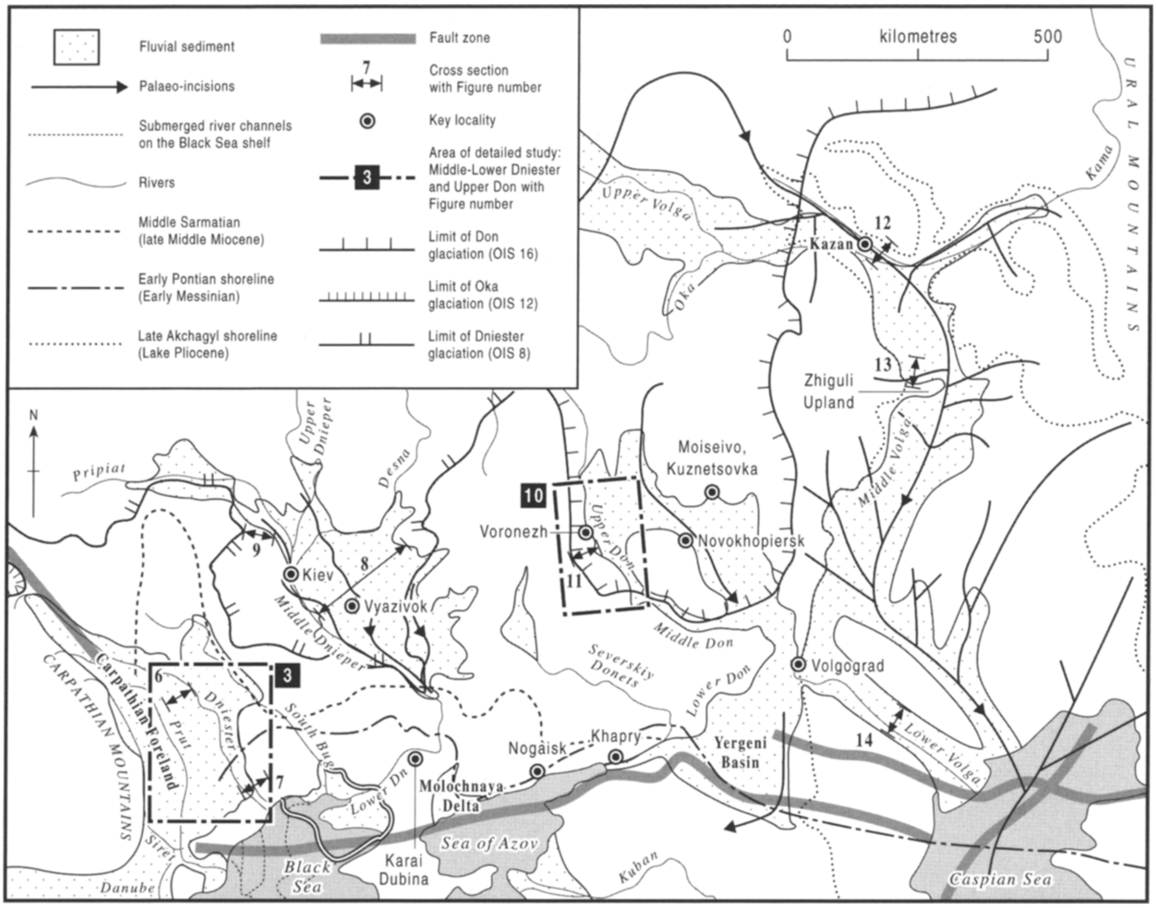


Fig. 1. Map of the study region, showing the main fluvial formations of the central and southern part of the East European Plain, including present and former courses of major rivers in relation to limits of former Pleistocene ice sheets and present and former positions of the Black and Caspian Sea coastlines. The Lower Volga is defined as the reach downstream of Volgograd, the Middle Volga being the reach between Kazan and Volgograd. Double line on the northern Black Sea shelf indicates the southern margin of the Early–Middle Pleistocene Dnieper Delta basin. The important fluvial sites depicted outside the areas covered by later, more detailed, maps are (see also Fig. 2): Kuznetsovka, the stratotype of the Muchkap Suite; Moiseivo and Novokhopiersk, stratotypes of the Yuzhnovoronezh Series; Khapry, the stratotype of the Khapry (Late Pliocene) faunal assemblage; and Nogaisk, a site with the Taman (Early Pleistocene) faunal assemblage. Sources of data include Chugunny (1965), Goretskiy (1966, 1982), Rodzyanko (1970), Holmovoi (1974), Chirka (1974), Scherbakov *et al.* (1976), Obedientova (1977), Iossifova (1977), Brylev (1978), Freedman (1984), Zastrozhnov (1991), Bilinkis (1992) and Matoshko *et al.* (2002).

Pliocene); and the Apsheron (*c.* 1.8–0.8 Ma), equivalent to the Early Pleistocene. Other chronologies indicate slightly different ages, for instance the start of the Akchagyl is 3.4 Ma in the scheme by Zhamoida *et al.* (2000); Fig. 2).

The Black Sea is connected at present to the global marine environment through the Bosphorus and Dardanelles straits and seems to have been similarly connected during other Middle–Late Pleistocene interglacials (e.g. Tchepalyga, 1997). Except for other possible brief periods of connection around the Pontian–Dacian boundary (e.g. Hsü & Giovanoli, 1979), the Black Sea has formed a lacustrine environment at all times since the Middle Miocene. In contrast, the Caspian Sea has probably not been connected to the global marine environment at any stage since then, although it was connected to the Black Sea during the Sarmatian, Meotian, early Pontian and the middle part of the Akchagyl stage (e.g. Illina *et al.*, 1976; Semenenko, 1993; Mitchell & Westaway, 1999), during the Palaeo-Euxinian and Khazar stages of the Middle Pleistocene (Popov, 1961; Fedorov, 1978; Goretskiy, 1982) and during the latest Pleistocene (Dodonov *et al.*, 2000). Its level has, instead, fluctuated in response to varying runoff from Eastern Europe (i.e. from the Volga) and central Asia; it was typically low during the Kimmerian, leading to major incision by the Volga (Table 2), but increased during parts of the Akchagyl and Apsheron stages. For instance, in the Late Akchagyl stage a highstand of the

Table 1. Summary of the main fluvial accumulations in this study region.

Name	Age of sediment	Thickness (m)
Carpathian Foreland Basin[a]	Miocene–Holocene	70–135
Pripiat Basin	Middle Pleistocene–Holocene	15–20
Upper Don Valley	Pliocene–Holocene	60–85
Middle Dnieper Basin	Miocene–Holocene	70–80
Dnieper Delta	Early–Middle Pleistocene	85–100
Molochnaya Delta	Pliocene–Holocene	20–30
Severskiy Donets Basin	Pliocene–Holocene	70–80
Yergeni Upland[b]	Miocene–Pliocene	50–70
Upper Volga Basin	Middle Pleistocene–Holocene	40–60
Middle Volga Valley	Early Pleistocene–Holocene	100–110
Lower Volga Valley	Early Pleistocene–Holocene	70–80

Figure 1 shows the locations of the basins. Data are summarized from the same sources as Figure 1.
[a]Carpathian Piedmont 'Sheet' and Dniester Valley.
[b]Yergeni 'Sheet'.

Caspian Sea flooded the Volga palaeo-valley northward to the vicinity of Kazan (Fig. 1), blanketing a large region with clay that now provides a useful stratigraphic marker. Although not truly marine, it is customary in the regional stratigraphy to designate sediments deposited in the Caspian Sea as 'marine'; this usage is followed here.

In 1956, the absence of reliable age control led to the Interdepartmental Stratigraphic Committee of the former USSR designating both the Akchagyl and Apsheron stages as 'Pliocene'. The Akchagyl stage is currently best defined by magnetostratigraphy (e.g. Gurariy *et al.*, 1977), starting at the Gilbert–Gauss geomagnetic polarity reversal (*c.* 3.6 Ma) and ending at or just before the basal Olduvai reversal (*c.* 1.95 Ma; oxygen isotope stage (OIS) 72; e.g. Hilgen, 1991). Some more recent studies (Castradori, 1997; Zhamoida *et al.*, 2000) have suggested instead that the end of the Akchagyl be placed within the Olduvai subchron (*c.* 1.8 Ma; OIS 65). The end of the Apsheron stage is at or just after the Matuyama–Brunhes reversal, which occurred at *c.* 0.78 Ma, during OIS 19. Thus, in terms of the current international definitions, the Akchagyl roughly coincides with the Middle–Late Pliocene but the Apsheron is roughly equivalent to the Early Pleistocene (Fig. 2). The authors aim to elucidate the main approaches and the key results of important studies of fluvial formations within a major part of Eastern Europe, an area that remains little known today outside the countries of the former USSR. This paper attempts an up-to-date summary using a common baseline, while also indicating the principal remaining problems that await further investigation.

Table 2. The main Miocene–Pliocene incision events.

Name	Age of incision	Incision (m)
Palaeo-Dnieper	Miocene–Pliocene	45
Palaeo-Don	Late Miocene (Pontian)	80–120
Palaeo-Volga	Early Pliocene (Cimmerian)	150–200

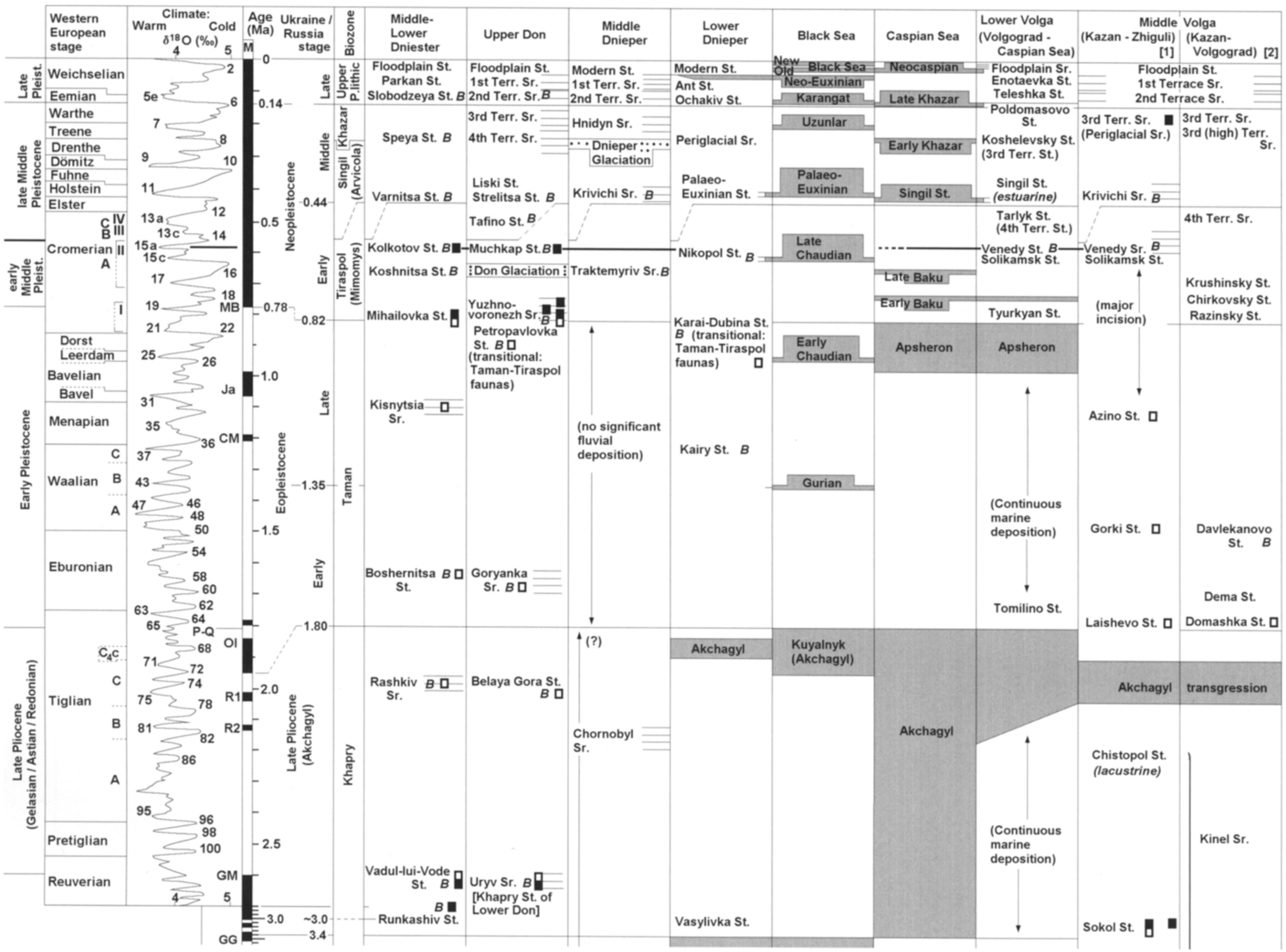
Figure 1 shows the locations of these river courses during these incision phases. Data are summarized from the same sources as Figure 1.

2. APPROACHES TO THE STUDY OF FLUVIAL FORMATIONS

Several informal current approaches to the geological study of the Late Cenozoic fluvial formations of the given territory can be distinguished. One of these was elaborated by Goretskiy (1966, 1970) and then used by others (Grischenko, 1976; Gozhik, 1982; Bukatchuk *et al.*, 1983; Freedman, 1984; Bilinkis, 1992; Matoshko & Chugunny, 1993). A key point of this approach is the identification, on the basis of mode of occurrence and lithological features, of alluvial dynamic facies and the depositional suites formed by them. It has been supplemented by palaeontological studies. Goretskiy applied his method to buried alluvial strata of Lower and Middle Pleistocene age, comparing and linking areas where detailed borehole evidence was available, then linking sections throughout the valley.

Another approach centres on traditional stratigraphy and the study of key sites (Tchepalyga, 1967; Markova, 1982; Bludorova & Fomicheva, 1985, Gozhik, 1992; Holmovoi *et al.*, 1985; Michailesku & Markova, 1992; Rekovets, 1994). Fluvial as well as overlying and underlying deposits are investigated by palaeontological and lithological methods, along with geochronology. In this way a well-founded detailed identification of the section units is possible. This approach, however, sometimes neglects such factors as section position (topography; main river or tributary), facies structure and burial conditions of different fauna or plant remnants in relation to fluvial processes (taphonomy).

The bulk of the available information about fluvial deposits is derived from geomorphology, by recognizing river terraces and correlating them by their height


Western European stage
Climate: Warm Cold δ18O (‰) 4 5
Age (Ma)
M
Ukraine / Russia stage
Biozone
Middle-Lower Dniester
Upper Don
Middle Dnieper
Lower Dnieper
Black Sea
Caspian Sea
Lower Volga (Volgograd - Caspian Sea)
Middle Volga (Kazan - Zhiguli) [1]
(Kazan-Volgograd) [2]
Late Pleist.
late Middle Pleistocene
early Middle Pleist.
Early Pleistocene
Late Pliocene (Gelasian / Astian / Redonian)
Weichselian
Eemian
Warthe
Treene
Drenthe
Dömitz
Fuhne
Holstein
Elster
C IV
B III
Cromerian II
A
I
Dorst
Leerdam
Bavelian
Bavel
Menapian
Waalian
Eburonian
Tiglian
C4c
Pretiglian
Reuverian
0
0.14
0.44
0.5
0.78
0.82
1.0
1.35
1.5
1.80
2.0
2.5
3.0
~3.0
3.4
MB
Ja
CM
P-Q
Ol
R1
R2
GM
GG
Neopleistocene
Eopleistocene
Late Pliocene (Akchagyl)
Upper P.lithic
Khazar
Singil (Arvicola)
Tiraspol (Mimomys)
Taman
Khapry
Floodplain St.
Parkan St.
Slobodzeya St. B
Speya St. B
Varnitsa St. B
Kolkotov St. B
Koshnitsa St. B
Mihailovka St.
Kisnytsia Sr.
Boshernitsa St. B
Rashkiv Sr. B
Vadul-lui-Vode St. B
B
Runkashiv St.
Floodplain St.
1st Terr. Sr.
2nd Terr. Sr. B
3rd Terr. Sr.
4th Terr. Sr.
Liski St.
Strelitsa St. B
Tafino St. B
Muchkap St. B
Don Glaciation
Yuzhno-voronezh Sr. B
Petropavlovka St. B
(transitional: Taman-Tiraspol faunas)
Goryanka Sr. B
Belaya Gora St. B
Uryv Sr. B
[Khapry St. of Lower Don]
Modern St.
1st Terr. Sr.
2nd Terr. Sr.
Hnidyn Sr.
Dnieper Glaciation
Krivichi Sr. B
Traktemyriv Sr. B
(no significant fluvial deposition)
(?)
Chornobyl Sr.
Modern St.
Ant St.
Ochakiv St.
Periglacial Sr.
Palaeo-Euxinian St.
Nikopol St. B
Karai-Dubina St. B (transitional: Taman-Tiraspol faunas)
Kairy St. B
Akchagyl
Vasylivka St.
New Old Black Sea
Neo-Euxinian
Karangat
Uzunlar
Palaeo-Euxinian
Late Chaudian
Early Chaudian
Gurian
Kuyalnyk (Akchagyl)
Neocaspian
Late Khazar
Early Khazar
Singil St.
Late Baku
Early Baku
Apsheron
Akchagyl
Floodplain Sr.
Enotaevka St.
Teleshka St.
Poldomasovo St.
Koshelevsky St. (3rd Terr. St.)
Singil St. (estuarine)
Tarlyk St. (4th Terr. St.)
Venedy St. B
Solikamsk St.
Tyurkyan St.
Apsheron
(Continuous marine deposition)
Tomilino St.
(Continuous marine deposition)
Floodplain St.
1st Terrace Sr.
2nd Terrace Sr.
3rd Terr. Sr. (Periglacial Sr.)
Krivichi Sr. B
Venedy Sr. B
Solikamsk St.
(major incision)
Azino St.
Gorki St.
Laishevo St.
Akchagyl
Chistopol St. (lacustrine)
Sokol St.
3rd Terr. Sr.
3rd (high) Terr. Sr.
4th Terr. Sr.
Krushinsky St.
Chirkovsky St.
Razinsky St.
Davlekanovo St. B
Dema St.
Domashka St.
transgression
Kinel Sr.

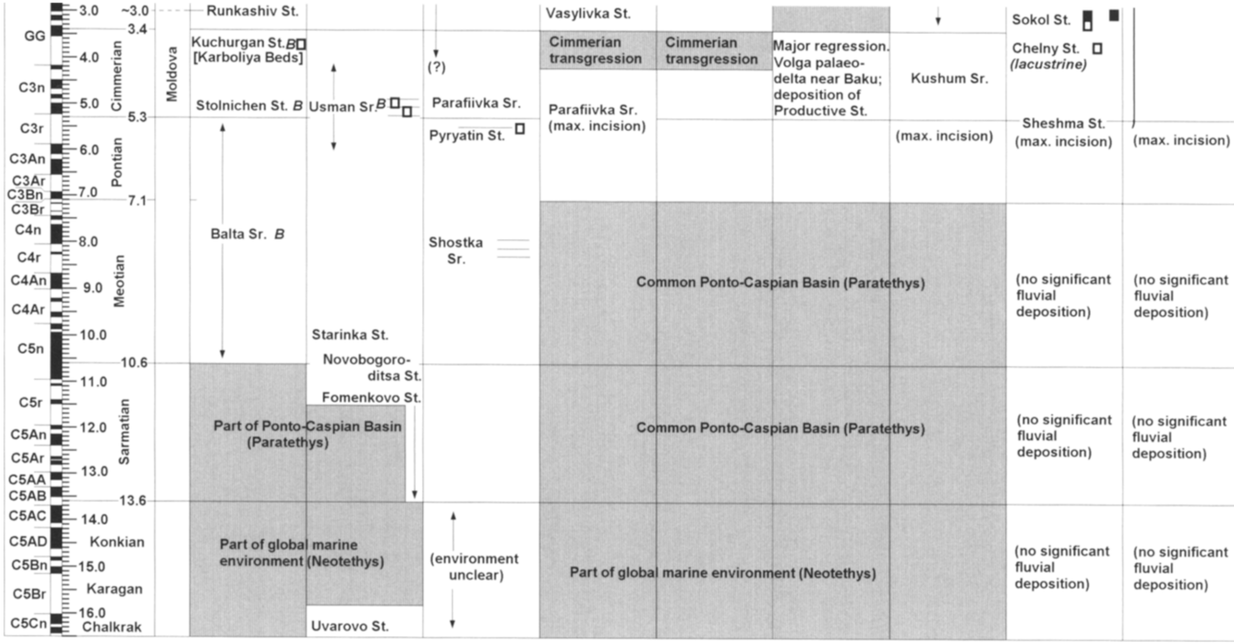


Fig. 2. Stratigraphical correlation between the main regions mentioned in this study, summarizing the results of Goretskiy (1966), Sukhov (1970), Velichko *et al.* (1983), Gozhik (1984), Tchepalyga *et al.* (1986), Vasiliev (1986), Semenenko (1993), Dodonov *et al.* (2000), Matoshko *et al.* (2002) and Shick *et al.* (2002). The oxygen isotope record is from Shackleton *et al.* (1990). Interpreted Central and Western European stratigraphical stage names are adapted from Westaway *et al.* (2002). Mio-Pliocene magnetostratigraphy is from Steininger *et al.* (1996). The thick line crossing the figure in the Middle Pleistocene marks the *Mimomys–Arvicola* transition, the boundary between the Tiraspol and Singil bizones of Ukraine/Russia, equivalent to the Biharian–Toringian boundary in Central Europe. Notes: (1) Two interpretations are shown for the Middle Volga – [1] is from Goretskiy (1966) and Bludorova & Fomicheva (1985) while [2] is from Shick *et al.* (2002). (2) The Yuzhnovoronezh Series of the Don corresponds to (from old to young) the Pokrovka, Illiinka and Novohopiersk suites in the Krasnenkov *et al.* (1984) scheme and the Pokrovka, Kalach and Veretie suites in the Iossifova (2001) scheme. (3) In a new correlation scheme (Shick *et al.*, 2002) the Venedy and Solikamsk suites are absent in the Lower Volga, like in the Middle Volga (interpretation [2]). (4) The Kushum Series is established only in the NE part of the Lower Volga region. (5) As is indicated in the text, the Apsheron stage has been officially 'defined' as Pliocene but is, in fact, Early Pleistocene or 'Eopleistocene' in the local terminology (Zhamoida *et al.*, 2000). (6) The Early Baku marine deposits, indicating a highstand of the Caspian Sea, pre-date the Solikamsk Suite of the Volga and are, thus, early Middle Pleistocene. According to Shick *et al.* (2002), the Early Baku stage correlates with the second and third suites of the Yuzhnovoronezh Series of the Don; and the beginning of the Late Baku stage correlates with the Don glacial horizon. Open and closed squares denote reversed and normal geomagnetic polarities (respectively).

above river level. This approach has been improved and elaborated upon in recent decades (Volkov & Sokolovskiy, 1976; Obedientova, 1977) but, for it to be a reliable technique, an accompanying geological investigation is required. Its application in isolation is probably a key reason for the great divergence of opinions on the nomenclature, age and occurrence of the river terraces within each valley. Many terraces are formed by several superimposed alluvial suites and their sections include non-fluvial deposits. In these cases the prevailing use of the term 'river terrace' to mean the alluvial sediment body is incorrect. The present authors apply this term only to fluvial landforms.

A further method worthy of note is that suggested by Veklich & Dubniak (1975). In their opinion most terrace alluvium has a two-fold structure. The uppermost alluvial strata pass upwards into loess with a subaerial soil developed in its upper part and further burial by a sequence of younger loesses and soils. The upper alluvial suite of a terrace was generally formed during a cold stage, directly prior to the onset of aeolian loess sedimentation, while the lower alluvial member dates from the preceding warm stage. Thus, the alluvium of a terrace corresponds to a certain loess–soil couplet on interfluve areas, i.e. to a particular climatic cycle. A problem with this approach is that evidence from the fluvial facies themselves is neglected in favour of simplistic climato-stratigraphy.

The present review combines data from all these different approaches, with the exception of the last. Exhaustive summaries are not possible within the constraints of this article and, to achieve a compatible story, modifications have been made according to approved principles (Matoshko *et al.*, 2002). Among the vast diversity of fluvial data, attention has been concentrated on the most studied areas of the main rivers, supplemented, where appropriate, by important data from their tributaries.

3. MODE OF OCCURRENCE AND RELATION TO LANDFORMS

The most informative evidence about ancient fluvial systems comes from their sediments. From Figure 1 it is clear that these had distribution patterns in the past that sometimes differed from the modern drainage. These sediments are illustrated here grouped by river systems, for the Dniester (Figs 3–7), the Dnieper (Figs 8, 9; see also Matoshko *et al.*, 2002), the Don (Figs 10, 11) and the Volga (Figs 12–14). The largest of these accumulations can be divided into infills, deltas and 'sheets'. Deep infills occupy incised canyon-like palaeo-valleys (e.g the Middle and Lower Volga and the Upper Don; a few tens of kilometres wide) infilled by fluvial, deltaic and estuarine Miocene–Pliocene deposits (e.g. Fig. 12). Other substantial infills occupy wider palaeo-valleys (e.g. the alluvial basins of the Upper Volga, Pripiat, Middle Dnieper and Severskiy Donets). The term 'sheet' can be used to refer to fluvial sediment bodies covering large areas, with a generally uniform thickness (Table 1) that is, at most, one thousandth of their lateral extent. The deltas of the Volga, Don, Molochnaya and Dnieper, as well as the 'sheets' of the Yergeni Upland (Yergeni Delta; Fig. 1) and the Carpathian Piedmont (Carpathian Foreland Basin; Table 1), are predominantly superimposed onto subhorizontal surfaces without substantial incision.

The alluvial accumulations can have different expressions in the modern surface. Often, they are buried beneath younger fluvial, aeolian, slopewash or glacial deposits. For example, the complex of Miocene–Pliocene fluvial and overlying deposits forms, in the modern valley of the Middle Dnieper, a single inclined surface, sloping westwards from a plateau at 170–150 m to 110–100 m above sea-level (asl) (Matoshko *et al.*, 2002; Fig. 8). The analogous accumulations of the Upper Don have the same relief expression (Holmovoi *et al.*, 1985). Younger river terraces are better expressed in the landscape. Only the suites that post-date the Dnieper Glaciation (OIS 8) form distinct staircases in the Volga, Dnieper and Don valleys.

The 'sheet' of the Carpathian Piedmont is formed by the Upper Miocene alluvium of the Balta Series, occupying the vast area of the present South Bug–Dniester interfluve. The oldest Pliocene alluvium survives in the form of numerous small fragments in the highest parts of the modern Dniester–Prut–Siret interfluves (Bilinkis, 1992). In contrast, the Upper Pliocene and Quaternary fluvial deposits of the Dniester and other Carpathian rivers are represented by cut-and-fill terrace staircases, with up to 13 steps, easily discernible in the sides of their deeply incised valleys (Figs 4–7). Further east, the Yergeni channel and overbank alluvial sands form the substrate of the Yergeni Upland at 70–140 m asl. According to Zastrozhnov (1991), these sands were produced by the southward-flowing Upper Miocene/Lower Pliocene Don and then uplifted before the Akchagyl (Upper Pliocene) and Apsheron (Lower Pleistocene) marine (Caspian) transgressions. The tops of the Akchagyl and Apsheron deposits, which are absent from the Yergeni Upland, are, in adjacent regions, at heights between 110 m asl and 180 m asl (Zastrozhnov, 1991). Despite the triangular shape of their outcrop, the Yergeni sands lack deltaic features; instead, their mode of occurrence and facies composition lead the present authors to interpret them as alluvial 'sheets'.

Within the lower reaches of the river courses, the lowest fluvial suites progressively sink beneath modern sea-level and are buried by estuarine, deltaic and marine deposits (Figs 7, 14). Although not studied in detail, there are interbedded fluvial, transitional and marine deposits typical of deltaic complexes (Fig. 14). The paucity of borehole data from the continental shelf means that the position and dimensions of deltas and, especially, of their older buried forms and offshore margins, are seldom clear. Multi-branched reaches of the modern lower Dniester and Dnieper systems adjoin

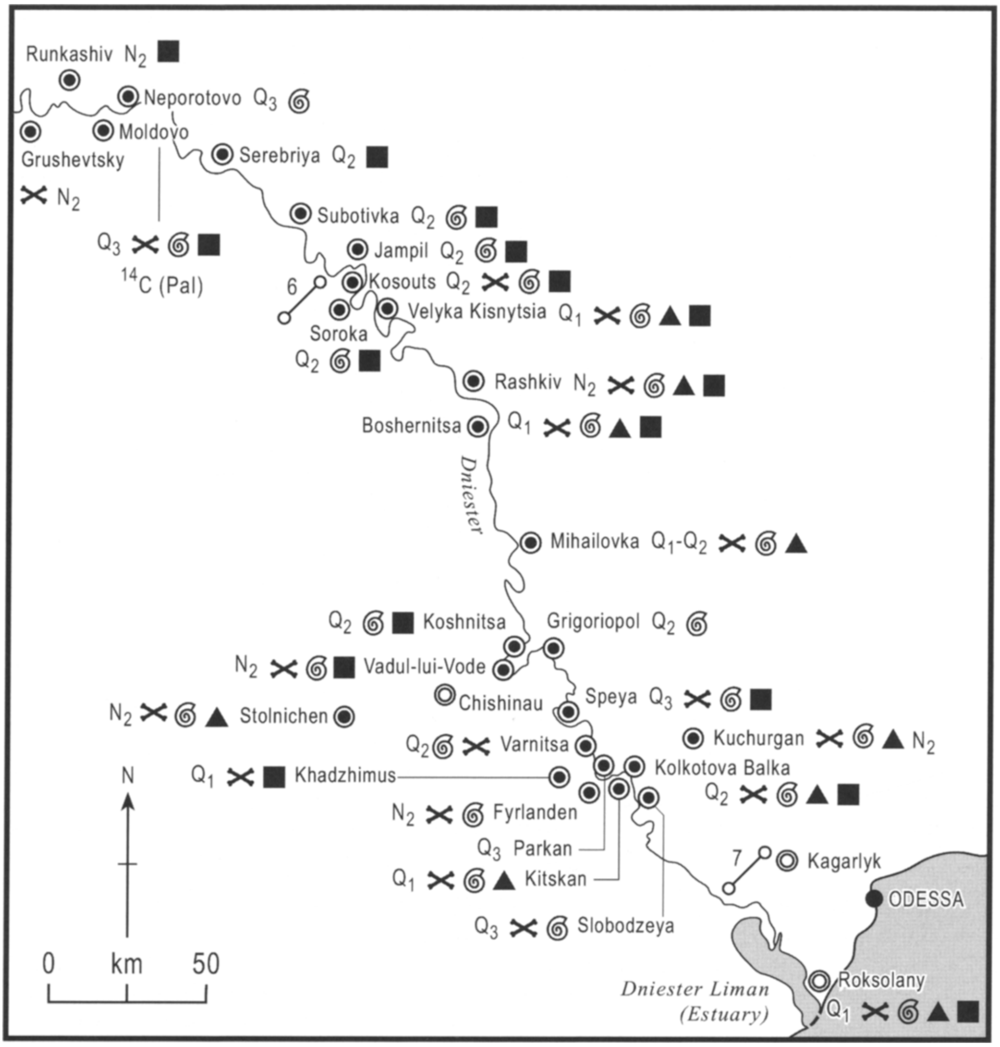


Fig. 3. Map of studied localities on the Middle–Lower Dniester, summarized from Tchepalyga (1967), Alexeeva (1977), Bukatchuk *et al.* (1983); Adamenko *et al.* (1986), Gozhik (1992) and Michailesku & Markova (1992). Letters denote ages of fluvial and related sediments: Q_3, Upper Pleistocene; Q_2, Middle Pleistocene; Q_1, Lower Pleistocene; and N_2, Pliocene. See Figure 4 for the meaning of other key symbols and Figure 1 for location.

'limans' (the local name for the estuaries, some of which are enclosed, of Ukrainian Black Sea rivers) that originated in the Late Pleistocene–Holocene. The large accumulative bodies of Lower–Middle Pleistocene deltas stretch out along the southern coast of the Dnieper–Bug liman, forming a complex stepped bathymetry. The Don has a narrow and elongated modern delta (Goretskiy, 1982), whereas the Volga has a modern delta of classic shape.

Continuations of the Dnieper, Dniester and Danube valleys, probably of Late Pleistocene age, can be traced across the northwestern part of the Black Sea shelf, almost to its outer edge (Fig. 1), and fluvial sediments are widespread on this part of the shelf (Scherbakov *et al.*, 1976).

Additional diversity of fluvial features in the study region includes the narrow canyons of the Middle Dniester and Lower Dnieper. There are also vast so-called internal fans near river confluences, the largest being at the confluence of the Pripiat and Dnieper (Matoshko, 1996). It has been established that the structure of such fans differs from the adjoining parts of the valley.

There is a clear correlation between the position of the largest Late Cenozoic fluvial formations and major tectonic structures. The central part of the Middle Dnieper alluvial basin coincides with the Dnieper–Donets Aulacogen (rift valley) and part of the Upper Volga basin coincides with the aulacogen in the central part of the Moscow Syncline. The major

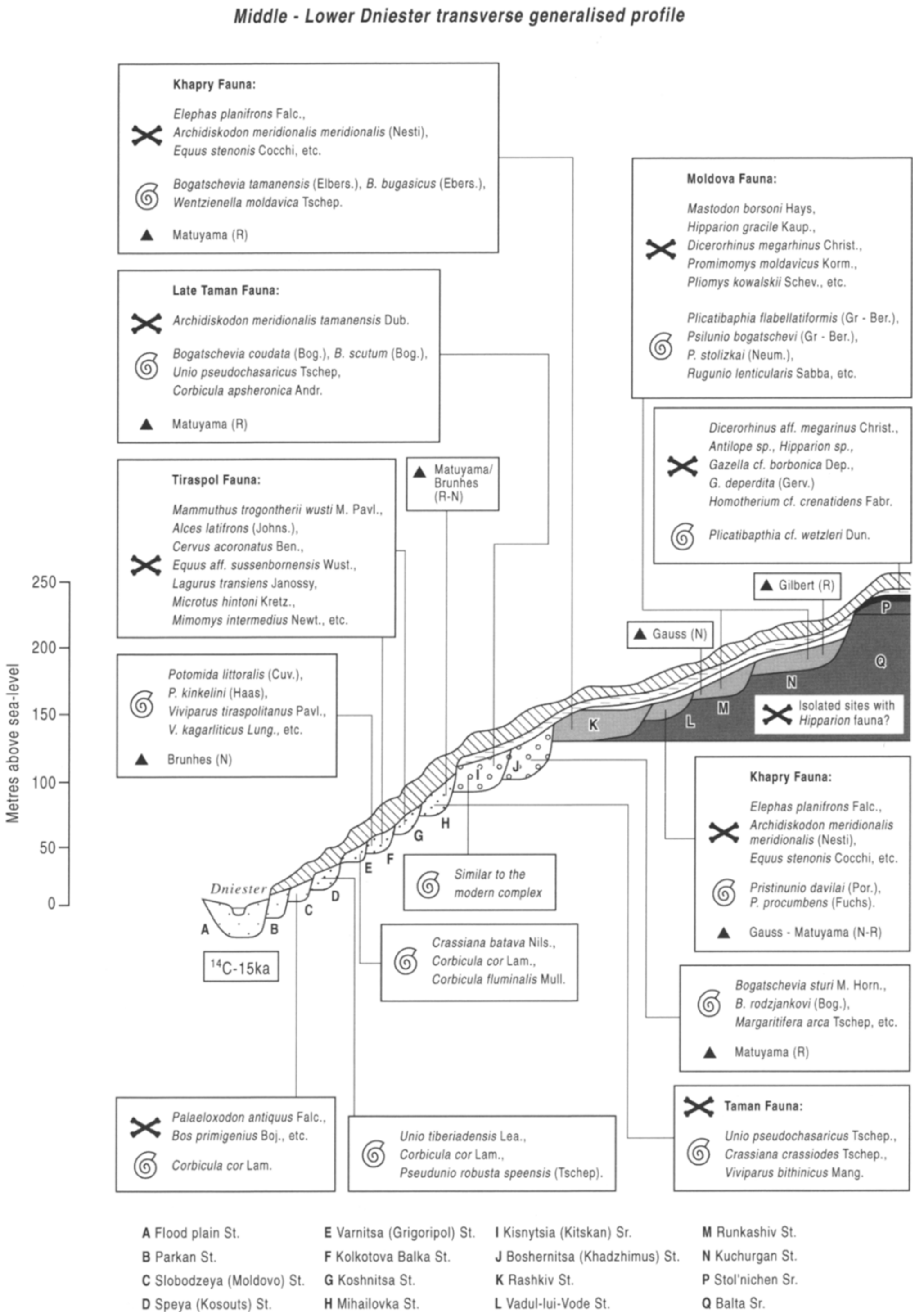

Middle - Lower Dniester transverse generalised profile
Khapry Fauna:
Elephas planifrons Falc.,
Archidiskodon meridionalis meridionalis (Nesti),
Equus stenonis Cocchi, etc.
Bogatschevia tamanensis (Elbers.), B. bugasicus (Ebers.),
Wentzienella moldavica Tschep.
Matuyama (R)
Late Taman Fauna:
Archidiskodon meridionalis tamanensis Dub.
Bogatschevia coudata (Bog.), B. scutum (Bog.),
Unio pseudochasaricus Tschep,
Corbicula apsheronica Andr.
Matuyama (R)
Tiraspol Fauna:
Mammuthus trogontherii wusti M. Pavl.,
Alces latifrons (Johns.),
Cervus acoronatus Ben.,
Equus aff. sussenbornensis Wust.,
Lagurus transiens Janossy,
Microtus hintoni Kretz.,
Mimomys intermedius Newt., etc.
Matuyama/
Brunhes
(R-N)
Potomida littoralis (Cuv.),
P. kinkelini (Haas),
Viviparus tiraspolitanus Pavl.,
V. kagarliticus Lung., etc.
Brunhes (N)
Moldova Fauna:
Mastodon borsoni Hays,
Hipparion gracile Kaup.,
Dicerorhinus megarhinus Christ.,
Promimomys moldavicus Korm.,
Pliomys kowalskii Schev., etc.
Plicatibaphia flabellatiformis (Gr - Ber.),
Psilunio bogatschevi (Gr - Ber.),
P. stolizkai (Neum.),
Rugunio lenticularis Sabba, etc.
Dicerorhinus aff. megarinus Christ.,
Antilope sp., Hipparion sp.,
Gazella cf. borbonica Dep.,
G. deperdita (Gerv.)
Homotherium cf. crenatidens Fabr.
Plicatibapthia cf. wetzleri Dun.
Gilbert (R)
Gauss (N)
Isolated sites with
Hipparion fauna?
Metres above sea-level
250
200
150
100
50
0
Dniester
A
B
C
D
E
F
G
H
I
J
K
L
M
N
P
Q
¹⁴C-15ka
Similar to the
modern complex
Crassiana batava Nils.,
Corbicula cor Lam.,
Corbicula fluminalis Mull.
Khapry Fauna:
Elephas planifrons Falc.,
Archidiskodon meridionalis
meridionalis (Nesti),
Equus stenonis Cocchi, etc.
Pristinunio davilai (Por.),
P. procumbens (Fuchs).
Gauss - Matuyama (N-R)
Bogatschevia sturi M. Horn.,
B. rodzjankovi (Bog.),
Margaritifera arca Tschep, etc.
Matuyama (R)
Palaeloxodon antiquus Falc.,
Bos primigenius Boj., etc.
Corbicula cor Lam.
Unio tiberiadensis Lea.,
Corbicula cor Lam.,
Pseudunio robusta speensis (Tschep).
Taman Fauna:
Unio pseudochasaricus Tschep.,
Crassiana crassiodes Tschep.,
Viviparus bithinicus Mang.
A Flood plain St.
B Parkan St.
C Slobodzeya (Moldovo) St.
D Speya (Kosouts) St.
E Varnitsa (Grigoripol) St.
F Kolkotova Balka St.
G Koshnitsa St.
H Mihailovka St.
I Kisnytsia (Kitskan) Sr.
J Boshernitsa (Khadzhimus) St.
K Rashkiv St.
L Vadul-lui-Vode St.
M Runkashiv St.
N Kuchurgan St.
P Stol'nichen Sr.
Q Balta Sr.

Fig. 4.

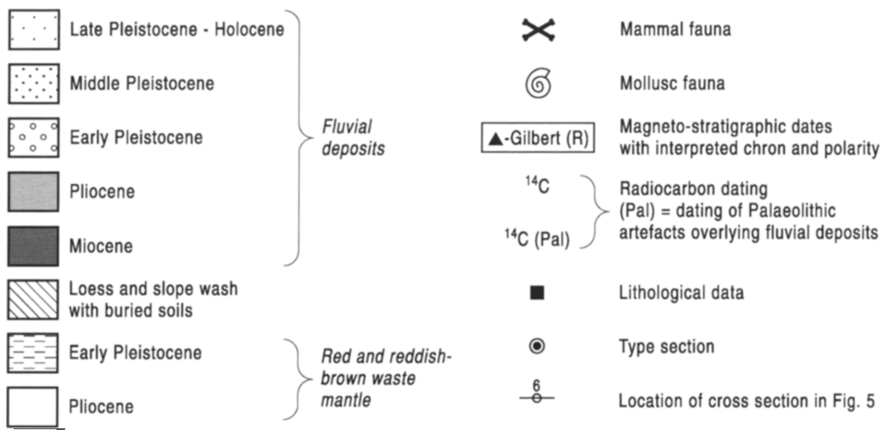


Fig. 4. *continued.*

Fig. 4. Generalized transverse profile through the Middle–Lower Dniester sediments (see Fig. 3 caption for sources), showing biostratigraphic and magnetostratigraphic dating evidence.

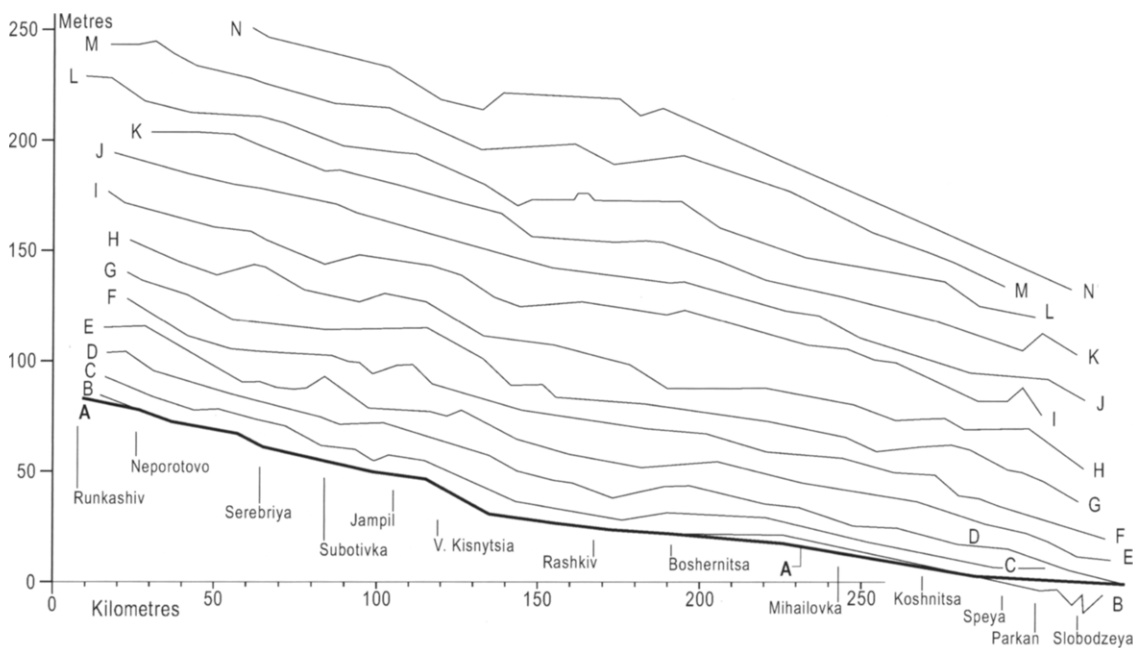


Fig. 5. Longitudinal profile, showing the fluvial deposits in the reach of the Middle and Lower Dniester depicted in Figure 3 (after Gozhik, 1992). Thick line A marks the modern profile of the Dniester. Thinner lines N to B mark the upper surfaces of Dniester terraces, labelled consistently with Figure 4.

deltas abut the marginal faults of the East European Platform (Fig. 1) and the fluvial 'sheet' of the Carpathian Piedmont extends along the Carpathian Foreland, bordering the orogenic belt.

4. FACIES AND LITHOLOGICAL CHARACTERISTICS

Dynamic alluvial facies (channel, overbank, abandoned channel) are represented by large lithologically uniform alluvial members, formed under similar conditions of sedimentation. There is a clear relationship between accumulation of bed- and suspended load, accumulation velocity and bedforms. These facies are stacked vertically or grouped together laterally to form alluvial suites, the suite reflecting an elementary cycle of fluvial erosion and sedimentation. The lack of regional breaks and uncomformities within suites is an important basis of their definition. Suite thickness ranges from 6 m to 40 m in the main valleys. Suites of

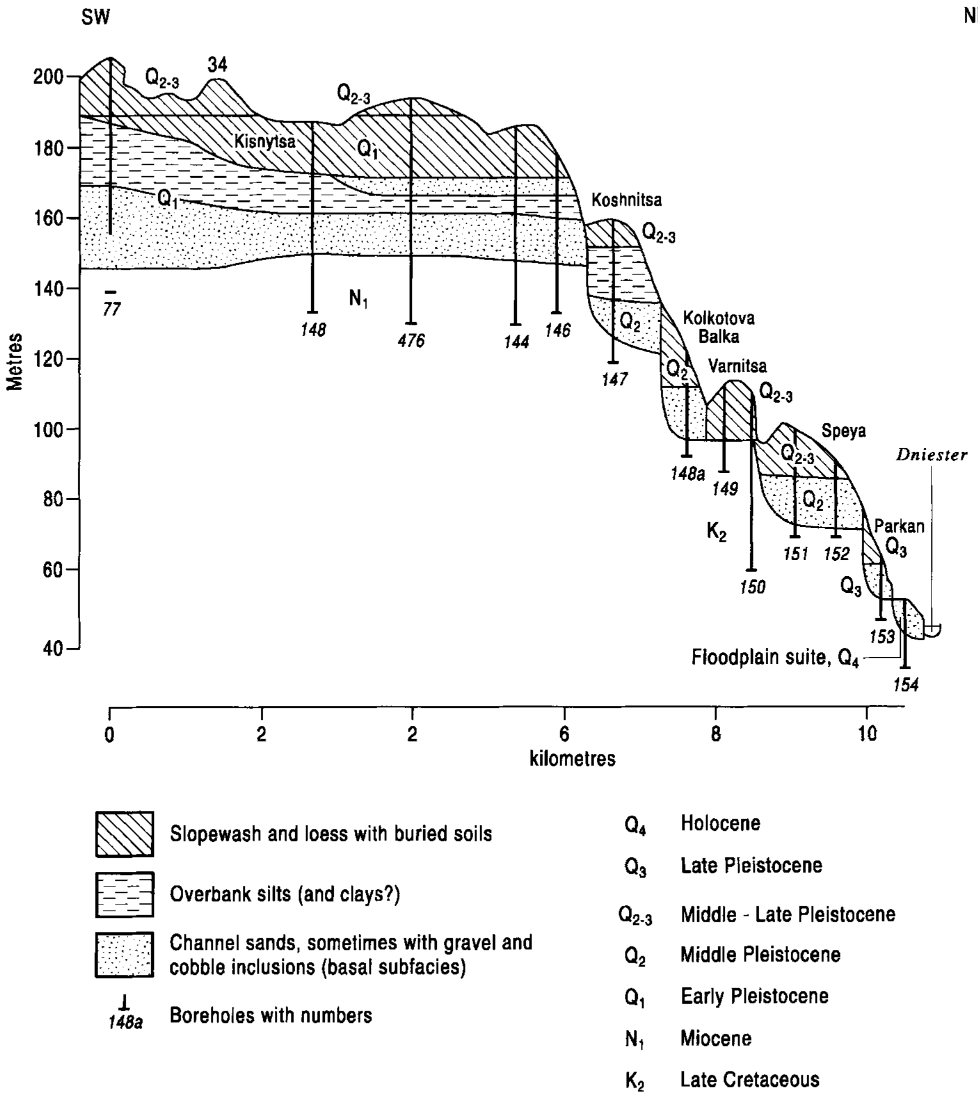


Fig. 6. Cross-section through Middle Dniester sediments near the village of Kosouts, Moldova (after Gozhik, 1992). See Figures 1 or 3 for location.

similar age and mutual relation combine to form series. The terms 'suite' and 'series' are cited in the present review according to the above definition, even where this differs from usage in primary sources (i.e. alluvial bodies previously called suites are referred to as series with the same names).

Series can consist either of cut-and-fill suites, associated with valley incision, or superimposed suites, associated with valley infill. Superimposed suites are generally thicker and some facies are reduced or absent in comparison with cut-and-fill suites. Most of the Dniester suites are of cut-and-fill origin (Figs 4, 6, 7), as are some late Middle Pleistocene and Upper Pleistocene–Holocene Volga, Dnieper and Don suites and some pre-Quaternary Dnieper and Don suites (Figs 8–14). Other alluvial suites are superimposed. In the Balta Series of the Dniester (Fig. 4) up to 11 cycles, which can be interpreted as superimposed suites, are distinguished (Bilinkis, 1992). The 4th terrace of the Upper Don (Fig. 11) and the Yergeni series (Lower Don) consist of at least four superimposed suites (Holmovoi *et al.*, 1985, Zastrozhnov, 1991).

Channel facies

In most Volga, Dnieper and Don suites, the channel facies consists of fine–medium sands, the coarsest of which are generally to found in the Upper Pleistocene–Holocene. In the Middle–Lower Dnieper the coarse

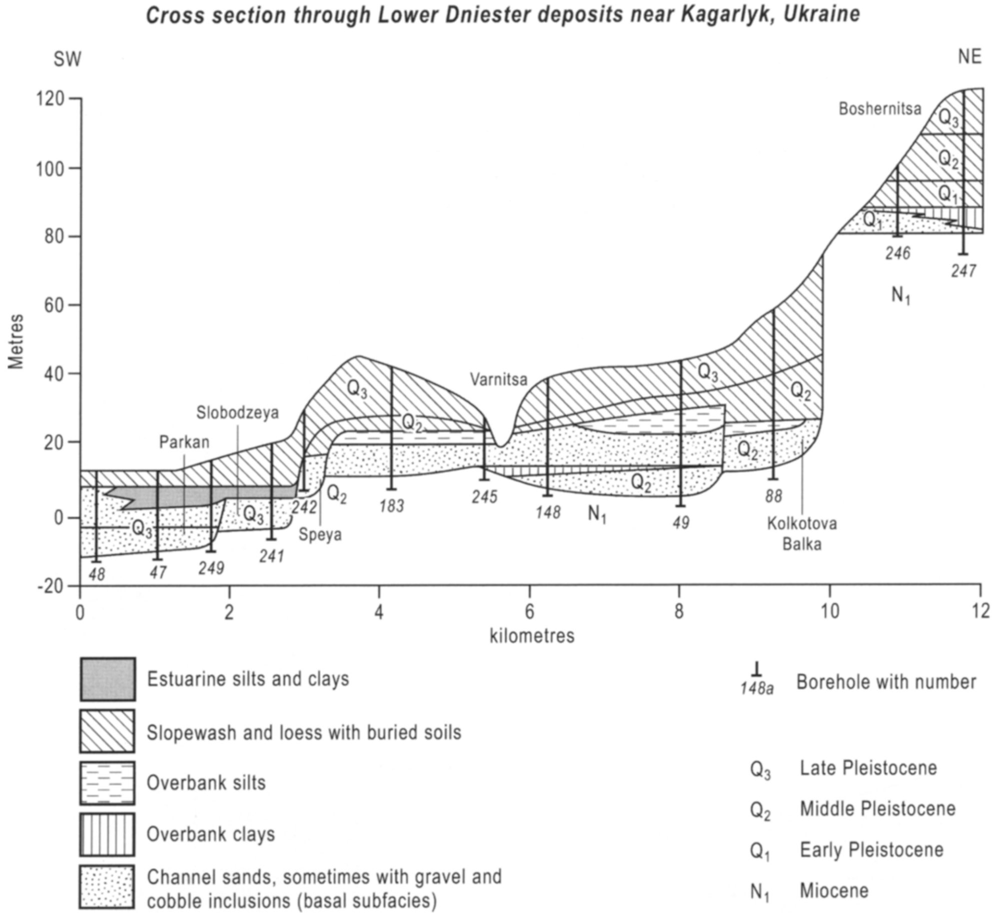


Fig. 7. Cross-section through Lower Dniester sediments near the village of Kagarlyk, Ukraine (after Gozhik, 1992). See Figures 1 or 3 for location.

fraction (>1.0 mm) is usually less than 1%, but increases where the deposits are in contact with the igneous and metamorphic rocks of the Ukrainian Shield. The content of fines (<0.1 mm) typically decreases from older to younger suites (Matoshko *et al.*, 2002). The channel facies of the Goryanka Suite (Lower Pleistocene, Upper Don) is represented by coarse sands and gravels with numerous clay balls (Holmovoi, 1974; Holmovoi *et al.*, 1985). This contrasts markedly with the particle-size distribution of other channel deposits of the platform rivers.

Upper Pliocene channel deposits of the Dniester are largely arenaceous (gravelly sand), giving way to predominantly rudaceous deposits in the Pleistocene, although the percentage of fines is high in both cases (Gozhik, 1992). Within the Upper Dniester, near the Carpathian Mountains, most suites consist of gravel or pebble-boulder mixes. Conglomerates form a part of the Kuchurgan Suite (Upper Pliocene) of the Lower Dniester. An increased content of coarse material, including large boulders, is characteristic of the Balta Series and the Varnitsa Suite (Middle Pleistocene). In the lower course of the Dnieper (Ant Suite) and Dniester (Kolkotov Suite, Slobodzeya Suite and Floodplain Series), channel facies are divided into two members (Gozhik & Novoselsky, 1989; Gozhik, 1992). In such cases the lower member consists of coarse poorly sorted basal material overlain by overbank deposits and occupies a narrow cut beneath the more widespread upper member, which consists predominantly of channel alluvium. Thus, the base of the same suite in neighbouring sections can be at different levels, according to whether both members are present or just the wider upper member is represented.

The Late Pleistocene and Holocene suites of the Lower Dnieper have more sand and coarse material, compared with equivalent-aged deposits of the Middle Dnieper. In contrast, the Upper Krivichi and Floodplain suites in the Middle and Lower Volga (Goretskiy, 1966) show a progressive downstream fining of channel sands and a parallel decrease in the

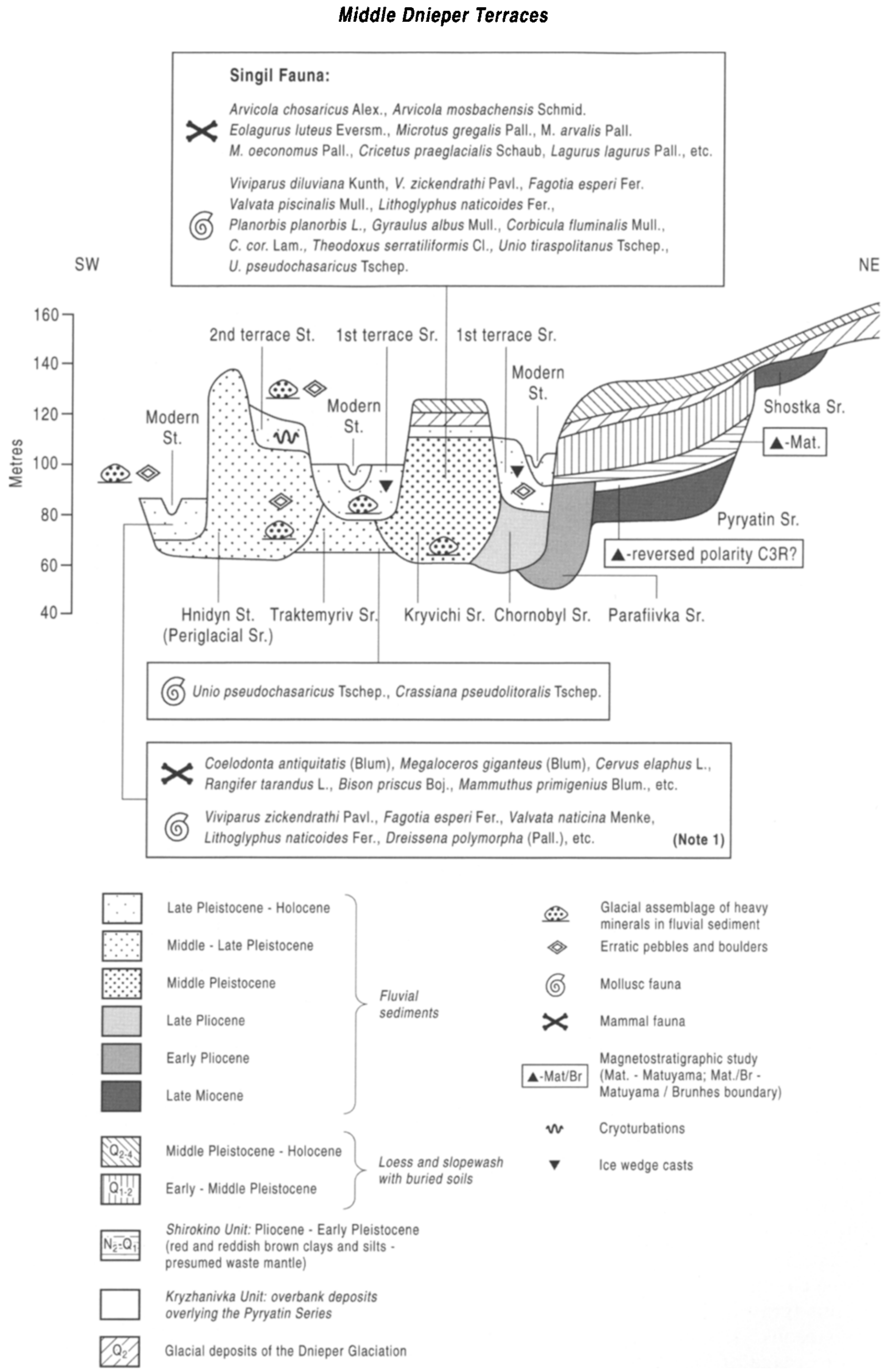


Fig. 8. Generalized transverse profile across the Middle Dnieper basin. This is based on a greatly simplified version of Matoshko *et al.* (2002, fig. 3), with added palaeomagnetic data from Vigilyanskaya (2001). Matoshko *et al.* (2002) also provided a longitudinal profile of the Middle and Lower Dniester terraces and other detailed maps and cross-sections for both reaches of this river, so these are not repeated here. Notes: (1) The listed fauna from the Modern Suite may include material reworked from the Hnidyn Series, 2nd Terrace Suite and 1st Terrace Series. (2) The depiction of the Chornobyl Series in this figure is schematic, to illustrate its stratigraphical position when projected into the adopted section line, which is otherwise a simplified version of Matoshko *et al.* (2002, fig. 3).

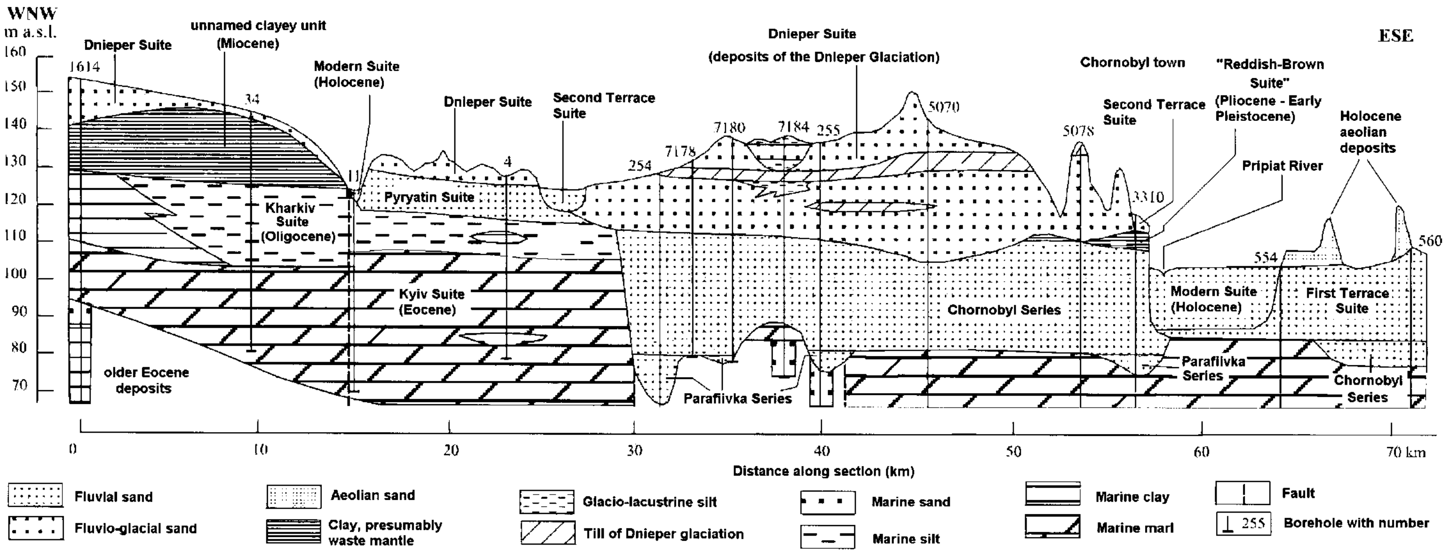


Fig. 9. Cross-section through the sediments of the Pripiat–Uzh interfluve, upstream of the Pripiat–Dnieper confluence near Chornobyl. See Figure 1 for location. Compiled by Matoshko using unpublished material from the State Geological Survey of the USSR. The deposit labelled 'unnamed clayey unit' consistes of clay (presumed waste mantle) interbedded with silt and sand. It is considered partly equivalent to the Late Miocene Parti-Coloured (Variegated) clays observed elsewhere in the Dnieper basin (see main text), although its uppermost part (not illustrated separately) corresponds to the 'Reddish-Brown Suite'. The Pripiat is locally at *c.* 103 m asl; the *c.* 10 m thick Pyryatin Suite reaches *c.* 130 m; the *c.* 10 m thick Parafiivka Series reaches *c.* 80 m; and is overlain by the c. 30 m Chornobyl Series that reaches c. 110 m. The local incision, by *c.* 40 m, between the top of the Pyryatin Series and the base of the Parafiivka Series is, thus, the same as in Figure 8, further down the Dnieper, even though the thicknesses of the sedimentary units are different.

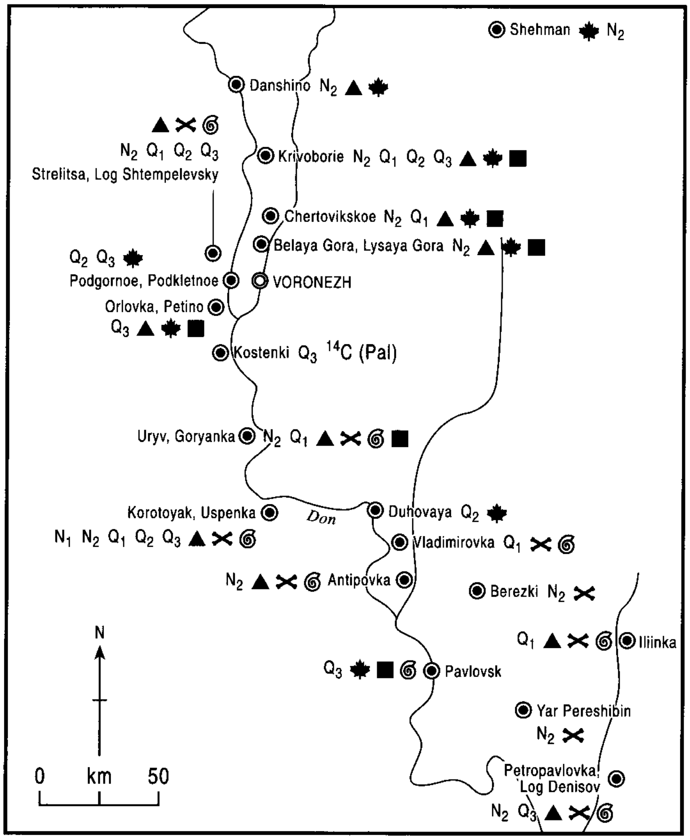


Fig. 10. Map of the reach of the Upper Don through the Middle Russian and Kalach Uplands around Voronezh, showing key fluvial sites representing sources of biostratigraphic and magnetostratigraphic age-control evidence. After Grischenko (1976), Krasnenkov *et al.* (1984), Holmovoi *et al.* (1985) and Praslov (1985), with modifications. Letters denote ages of fluvial and related sediments: Q_3, Upper Pleistocene; Q_2, Middle Pleistocene; Q_1, Lower Pleistocene; N_2, Pliocene; and N_1, Miocene. See Figure 11 for the meaning of other key symbols and Figure 1 for location.

number of silt lenses. Cross-sections within the Lower Volga (Goretskiy, 1966) reveal an almost total absence of coarse material. Detailed sampling of sections (at 0.2–1.0 m intervals) and analysis has sometimes shown a fining-upwards trend, although in other cases the particle-size distribution can remain stable or, typically at the top of superimposed series, it can coarsen upwards (Matoshko *et al.*, 2002). Cyclic changes in particle-size distribution (up to nine cycles) are seen in the Uryv Suite (Upper Pliocene) and Goryanka Suite (Lower Pleistocene) of the Upper Don (Holmovoi *et al.*, 1985).

The channel sands of the Middle and Lower Dnieper contain 93–99% quartz and 1–7% feldpspar, the latter being notably lower than in Upper Pleistocene–Holocene suites of the Upper Dnieper (Motuz, 1972; Barshchevskiy, 1977; Gozhik & Novoselsky, 1989; Matoshko *et al.*, 2002). The composition of the Yergeni sands (Upper Miocene–Lower Pliocene of the Don) is similar (Rodzyanko, 1970). The average quartz content of Dniester alluvium is 85–93%. The percentage of feldspar in the Middle Volga (Goretskiy, 1966) and Upper Don (Holmovoi *et al.*, 1985) is much larger than for the Dnieper. At the base of the Kinel Series (Lower Pliocene of the Volga) it rises to 50–70%, being 30–40% in the Pleistocene Suites of the Kazan' region (Bludorova & Fomicheva, 1985). A lower feldspar content is observed only in the sands of the Periglacial Series and in the 1st Terrace Suite (Goretskiy, 1966). Dniester and Dnieper sediments have less variable accessory mineral contents than those of the Volga. The Middle Dniester deposits are characterized by garnet, ilmenite, leucoxene and zircon. The alluvial deposits of the Upper Dniester have a large percentage of stable minerals. The Quaternary suites of the Dnieper, with the exception of the Traktemyriv Series, are characterized by a single ilmenite–garnet assemblage (Barshchevsky, 1977; Matoshko *et al.*, 2002), whereas each Volga suite (Goretskiy, 1966; Bludorova & Fomicheva, 1985) has a special set of accessory minerals. As a whole, stable minerals prevail in the heavy fractions of the Pliocene alluvium of the

Dnieper, Don and Volga. Increases of epidote (Volga) and amphiboles (Volga and Dnieper) from older to younger suites are noticeable, especially in the transition from Pliocene to Quaternary deposits.

Within the Middle Volga, particular assemblages of heavy minerals are indicators of a northern (Scandinavian) source (Bludorova & Fomicheva, 1985). These are recorded in most suites (Fig. 12), from the Laishevo Suite (Lower Pleistocene) onwards. Such assemblages, associated with far-transported glacial material, also occur in the Goryanka Suite (Lower Pleistocene) and the 4th Terrace and 3rd Terrace Series (Middle Pleistocene) of the Middle Don (Fig. 11). The dominance of the amphibole group (together with garnet) is a feature of the Hnidyn Suite (Middle Pleistocene, Middle Dnieper) incised into the Dnieper glacial complex (Saalian; =OIS 8). In comparison with the Upper Dnieper, the Middle Dnieper shows a decline in unstable mineral content in the suites that post-date the Dnieper glaciation (Matoshko *et al.*, 2002). The mineral composition of the Modern Suite of the Middle and Lower Dnieper shows little variation (Lazarenko, 1964).

Basal subfacies

A basal subfacies is often distinguished within channel sequences (Fig. 13), occurring locally in erosional scours or forming extensive sheets. In comparison with the channel alluvium, it contains increased amounts of silt-clay and coarse fractions and also material derived from the underlying rocks and deposits. In places it is represented by gravelly sands and gravel. The basal subfacies of the Floodplain Suite of the Upper and Middle Volga contains a greater abundance of coarse material than is the case with other suites of the platform rivers (Goretskiy, 1966). Exposures of this subfacies often reveal boulders, clay balls, mammalian bones, organic-rich lenses and tree trunks (the last only in younger suites). It is generally cross-bedded, although in most suites of the Middle Dniester it is characterized by pebble–boulder mixes in a sand matrix, lacking sedimentary structures.

The petrographic composition of the basal boulders and pebbles of Volga Quaternary sequences differs substantially from those in pre-Quaternary suites (Goretskiy, 1966). Coarse debris of igneous and metamorphic rocks of northern origin first appears in the Venedy Series (Lower Pleistocene). Carpathian jasper is an index rock for deposits of the Upper Pliocene and Quaternary of Carpathian rivers such as the Dniester (Bilinkis, 1992), but is absent in the Miocene and Lower Pliocene deposits. In the pre-Quaternary alluvium of the Middle Dnieper, however, the basal subfacies can rarely be distinguished. Distinct basal horizons containing local crystalline rocks and far-travelled erratic pebbles and boulders of different origin are characteristic of Quaternary Dnieper deposits (Fig. 8).

Overbank facies

An overbank (floodplain) facies forms the upper part of alluvial suites, typically accounting for 10–20% of total thickness, although it can be significantly more in some superimposed suites. Within the Dniester this facies has rarely been observed, even in exposures. In pre-Quaternary series, overbank deposits are separated from underlying channel sequences by sharp contacts and are represented predominantly by clays. Silts and silty sands prevail in Quaternary complexes, which are poorer in clays and much richer in sand in comparison with pre-Quaternary sediments. The clay fraction of the Pliocene lacustrine–alluvial and alluvial deposits of the Middle Dniester (Fig. 6), Middle Dnieper (Fig. 8) and Upper Don (Fig. 11) is dominated by montmorillonite, whereas in Quaternary suites hydromicas and minerals of the montmorillonite and kaolinite groups occur in various proportions (Vorona, 1969; Holmovoi *et al.*, 1985; Gozhik, 1992; Matoshko *et al.*, 2002).

The pre-Quaternary clays are massive, with unclear lamination or lacking sedimentary structures. They often include carbonate or ferruginous–manganese concretions. In contrast, the overbank deposits of the Quaternary suites are characterized by horizontally laminated silts and interlaminated silts and clayey sands graded downwards to the channel facies. In the Holocene Volga and Dnieper suites an overbank facies is often not distinguishable in borehole sections because of the high sand content and rarity of silt lenses. The same lack of overbank facies recognition may be associated with the perfunctory nature of core descriptions of the older alluvium.

Abandoned channel facies

The abandoned channel facies occurs locally as distinct large lenticular bodies that represent the pattern of ancient channels in plan. It comprises interbedded horizontally laminated sands and silts enriched by organic matter and peat. This facies is well known from the Krivichy Series (Middle Pleistocene of the Middle Dnieper) and in the Upper Pleistocene–Holocene suites of the Volga (Goretskiy, 1966). Lenses of the abandoned channel facies often mark the lateral contacts of suites.

Facies of problematic origin

In addition to the main dynamic facies considered above, some facies of problematic origin are distinguished. They occur separately or form a part of the established suites. The Periglacial Series of the Middle Volga, Periglacial Suite of the Upper and Lower Dnieper, Hnidyn Suite of the Middle Dnieper and also the Voronezh Fluvioglacial Ridge of the Upper Don have peculiar modes of occurrence and lithological features. The above-mentioned Volga

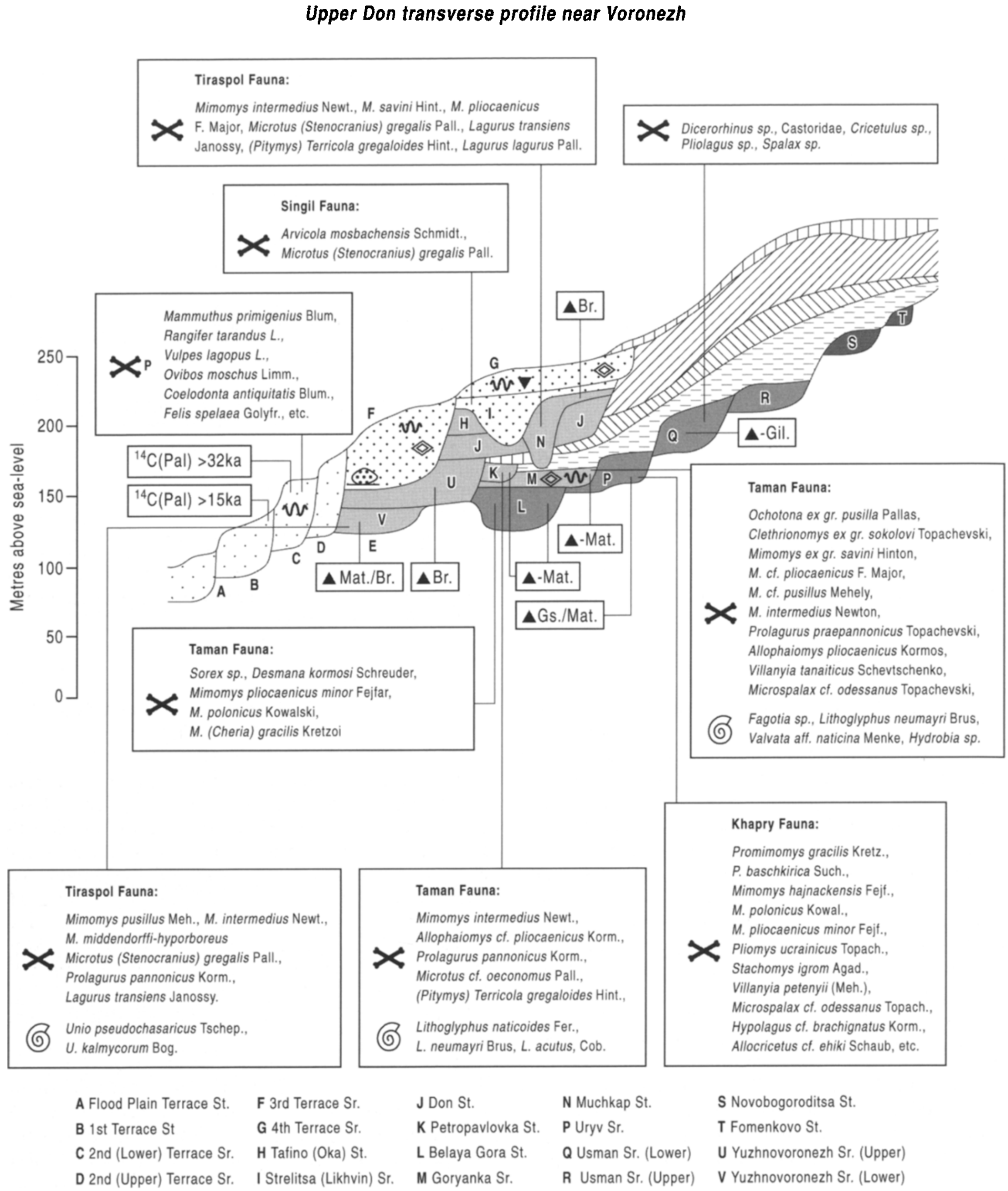


Fig. 11.

and Dnieper suites are associated with the start of valley aggradation following the Dnieper Glaciation (Goretskiy, 1970; Matoshko & Chugunny, 1993). Grischenko (1976) also referred the Voronezh Fluvioglacial Ridge to this time but later it was attributed to meltwater of the earlier (OIS 16) Don Glaciation (Holmovoi *et al.*, 1985; Fig. 2). These suites are expressed in the Don and Dnieper valleys as wide ridges and take the highest altitudinal position among Quaternary alluvial suites within all the rivers noted

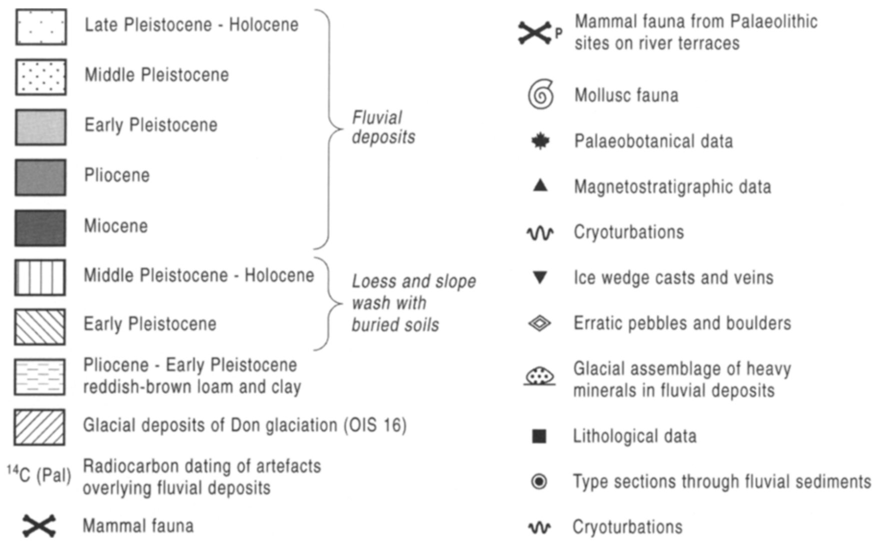


Fig. 11. *continued.*

Fig. 11. Schematic transverse profile across the Neogene and Quaternary deposits of the Upper Don in the Middle Russian and Kalach Uplands near Voronezh, showing sources of biostratigraphic and magnetostratigraphic age-control evidence. After Holmovoi *et al.* (1985), with additional data from Grischenko (1976), Krasnenkov *et al.* (1984), Praslov (1985), Kazantseva (1990), Iossifova (2001) and Agadjanian (2002). The species list for the Belaya Gora suite was determined by Holmovoi *et al.* (1985) from the Uryv 2a section. Palaeomagnetic epochs are: Gil., Gilbert; Gs./Mat., Gauss/Matuyama boundary; Mat., Matuyama, Mat./Br., Matuyama/Brunhes boundary; Br., Brunhes. See Figure 1 for location.

above. The ridges generally have gentle cross-cut profiles and wavy longitudinal profiles. Thick deposits of these suites cut into the glacial complex or overlie it in some places. Furthermore, the top of the Hnidyn Suite is higher than the top of the previous Krivichy Series and also higher than the cover of glacial deposits where these occur in the pre-glacial Dnieper valley (Fig. 8). In the Don and Volga valleys 'periglacial series', composed of horizontally bedded silty fine sands, are divided by silt and peat beds into several suites. In some places in the Middle Dnieper a thin layer of overbank facies occurs. Basal horizons are not distinguished and fossils are extremely rare.

In numerous cross-sections of the Volga and Dnieper, alluvial suites are replaced by thick clay deposits, mixed with silt or coarser material at their lateral contacts (Fig. 13). They are generally poorly sorted and contain numerous inclusions of materials resembling the deposits and rocks of the valley ledges. It is proposed that such deposits, enriched by local material, are called 'local contact facies'.

Parts of suites or their component members within the Kinel Series of the Volga (Fig. 12), as well as the Pyryatin series and the Krivichy Series of the Middle Dnieper (Fig. 8), are represented by lacustrine or fluvial deposits. In the main these are thick strata, uniform or interbedded with sands. Locally in the Middle Dnieper the lacustrine origin of deposits overlying the channel deposits of the Upper Krivichy Suite has been corroborated by sedimentological analysis.

5. STRATIGRAPHICAL SUBDIVISION AND CORRELATION

In this paper an attempt is made to combine the most systematic stratigraphical data from key rivers, based on the interpretations of the primary authors and the most recent suggested age correlations (see Figs 2, 4, 6, 7, 11, 13 and 14 and associated references). The stratigraphical positions of suites and series are established with reference to index beds and to palaeontological and magnetostratigraphic evidence. Several important type sections supply supplementary data. Mineralogical and petrographic age indicators are also of value for dating the alluvial suites (see above, 'Channel Facies').

It should be noted that there is a great regional difference in the detail of the stratigraphical studies. Complex and full data are available from the Middle/Lower Dniester and Upper Don, but information about many of the Don suites is derived from tributary sections, reducing the reliability of subdivision and age interpretation. The Dniester terrace staircase can, thus, be considered as the main fluvial stratotype for the East European Plain. The availability of palaeontological evidence from the Dnieper and Volga is significantly less. The Miocene/Pliocene fluvial stratigraphy of the Middle Dnieper, as with the Upper Pleistocene–Holocene of the Volga, Don and Dnieper, is based almost entirely on geomorphological data and relations with index beds (see below). There is also a large

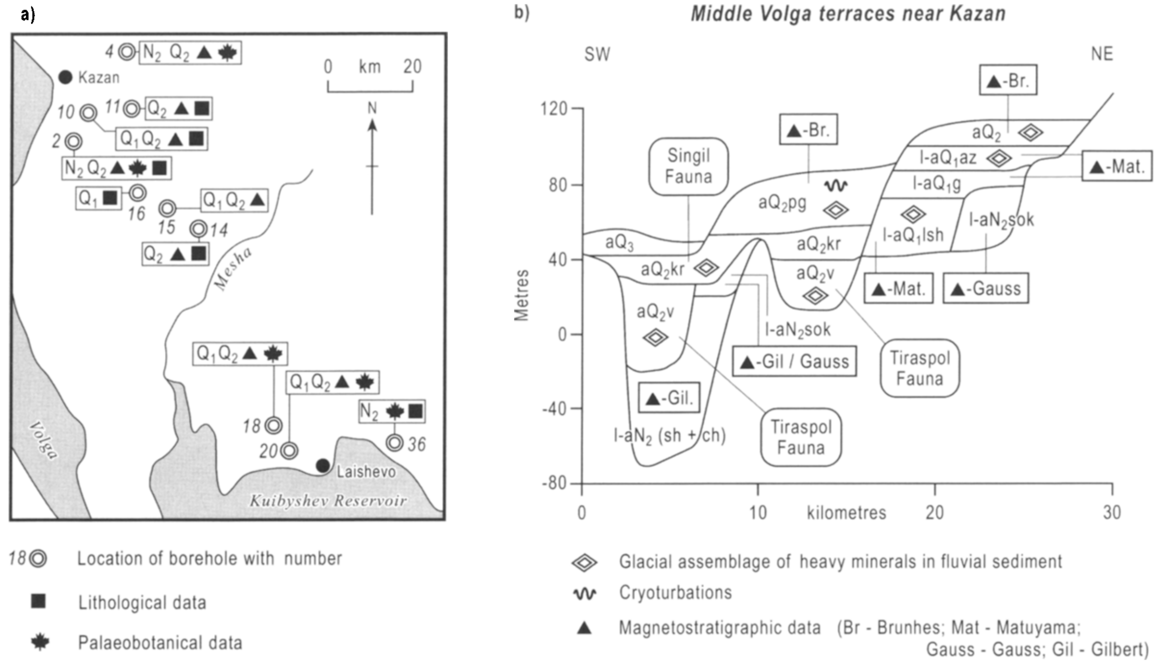


Fig. 12. (**a**) Map of and (**b**) cross-section through deposits of the upper Middle Volga near Kazan, after Bludorova & Fomicheva (1985) with modifications. See Figure 1 for location. The sequence, now flooded by the Kuibyshev Reservoir and, therefore, inaccessible is inset into Palaeogene sediments, which are not differentiated. Other sediments are labelled by symbols indicating the environment of formation, age and the name of each sedimentary unit. Environment codes are: a, fluvial; l-a, fluvio-lacustrine, non-stratified. Age codes are: N_2, Pliocene; Q_1, Lower Pleistocene; Q_2, Middle Pleistocene; Q_3, Upper Pleistocene. Name codes (Fig. 2) are: az, Azino Suite; g, Gorki Suite; kr, Krivichi Series; lsh, Laishevo Suite; pg, Periglacial Series; sh+ch, Sheshma Suite and Chelny Suite (i.e. the early part of the Kinel Series); sok, Sokol Suite; v, Venedy Series. Thus, for example, aQ_2kr means the Middle Pleistocene fluvial Krivichi Series. Notes: (1) The unnamed fluvial deposits labelled aQ_2 shown capping the Azino Suite ($l\text{-}aQ_1az$) were thought by Bludorova & Fomicheva (1985) to post-date the Venedy Suite (aQ_2v), indicating a major phase of aggradation after deposition of the latter. The present authors instead regard aQ_2 as older than the Venedy Suite, thus indicating a major phase of incision from the level of aQ_2 down to that of the Venedy Suite. The present authors anyway consider that the deposit labelled aQ_2 could possibly be aeolian, thus not providing any indication of the palaeo-river level. (2) According to the latest stratigraphical scheme (Shick *et al.*, 2002), the Laishevo Suite ($l\text{-}aQ_1lsh$) and Gorki Suite ($l\text{-}aQ_1$ g) are considered to be Late Pliocene, not Early Pleistocene. (3) In this reach of the Volga, the Solikamsk Suite (indicating the maximum Pleistocene incision) can be presumed to lie (outside the line of the cross-section) at a somewhat lower level than the Venedy Sr. (the same position as in the Zhiguli region, Fig. 13) and was not recorded in the research by Bludorova & Fomicheva (1985).

uncertainty with respect to the Early and Middle Pleistocene suites of the Middle and Lower Volga, the stratigraphy of which is currently under review (Shick *et al.*, 2002).

Index bed stratigraphy

The stratigraphic base of the Dniester fluvial sequence is determined by the top of the Sarmatian marine sediments (upper Middle Miocene/lower Late Miocene, from the isolated Paratethys Sea). The oldest of these fluvial deposits, the Balta Series, overlies the Sarmatian and is overlapped in the south by Pontian (Messinian) marine sediments. Equivalent deposits to the Balta Series occur at the base of the Yergeni Series (Lower Don). These Sarmatian and Pontian sediments can be distinguished by molluscan biostratigraphy. In the Middle Dnieper area, the characteristic deposits of the Novopetrov Suite (formerly known as the Poltava Series) and the overlying Parti-coloured Clays form the initial regional surface into which the oldest fluvial suites are incised (Fig. 9). These deposits contain very scarce faunal and plant remains and their genesis is ill defined. They are referred to the Miocene and correspond to the label 'Unclear Environment' in Figure 2.

The chronology of the earliest sediments of the Upper Don is poorly constrained. According to Krasnenkov *et al.* (1984), in uplands flanking the Middle and Upper Don, no Paratethyan 'marine' sediment of Sarmatian age is present. Instead, there is the fluvial Fomenkovo Suite of estimated Early Sarmatian age and the Middle Sarmatian Novobogoroditsa Suite. However, according to Iossifova (1977), in the Oka–Don plain (near the

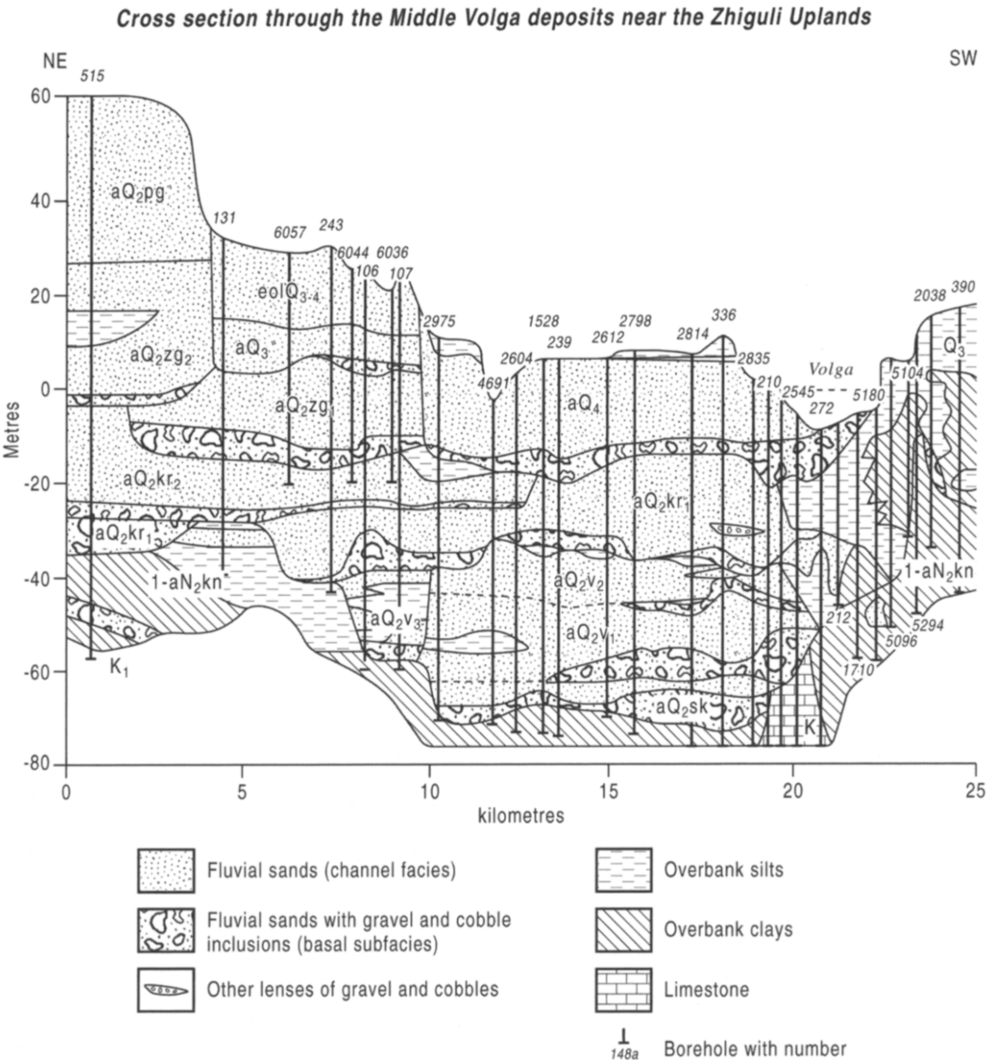


Fig. 13. Cross-section through the sediments of the lower Middle Volga near the Zhiguli Uplands (after Goretskiy (1966) with modifications). See Figure 1 for location. K denotes Cretaceous; K_1, Lower Cretaceous. Younger sediments are identified using the same notation as in Figure 12b. Environment codes are: a, fluvial; l-a, fluvio-lacustrine, non-stratified; and eol, aeolian. Age codes are: N_2, Pliocene; Q_2, Middle Pleistocene; Q_3, Upper Pleistocene; Q_{3-4}, Upper Pleistocene–Holocene; Q_4, Holocene. Name codes (Fig. 2) are: kn, Kinel Series; kr_1, Lower Krivichi Suite; kr_2, Upper Krivichi Suite; pg, Periglacial Series; sk, Solikamsk Suite; v_1, Lower Venedy Suite; v_2, Middle Venedy Suite; v_3, Upper Venedy Suite; zg_1, Lower Zhiguli Suite; zg_2, Upper Zhiguli Suite.

headwaters of the Don, *c*. 200 km south of Moscow), Paratethyan 'marine' sediment of Early–Middle Sarmatian age (the Gorelkina Suite) is followed by the fluvial Starinka Suite of Late Sarmatian–earliest Meotian age (Fig. 2). Krasnenkov *et al.* (1984) and Iossifova *et al.* (1977) considered that these deposits were followed by a prolonged period of non-deposition, followed by emplacement of the Usman Series in the Late Pontian and Cimmerian.

The marine (Caspian) Akchagyl deposits, spanning the Middle Pliocene to roughly the Plio-Pleistocene boundary, are an important marker throughout the Volga basin (see above). Their stratigraphical position is confirmed by pollen, molluscs and magnetostratigraphic data in the Lower Volga (Zhidovinov *et al.*, 1982), the Samara region (Konovalenko *et al.*, 1984) and the Bashkir piedmont of the Urals (Sidnev, 1984; Danukalova, 1996). Other marine marker deposits include those from the Apsheron, Baku and Khazar stages of the Lower–Middle Pleistocene in the Caspian Basin (Fig. 14) and the Late Pleistocene Neo-Euxinian (New Euxin) Stage of the Black Sea

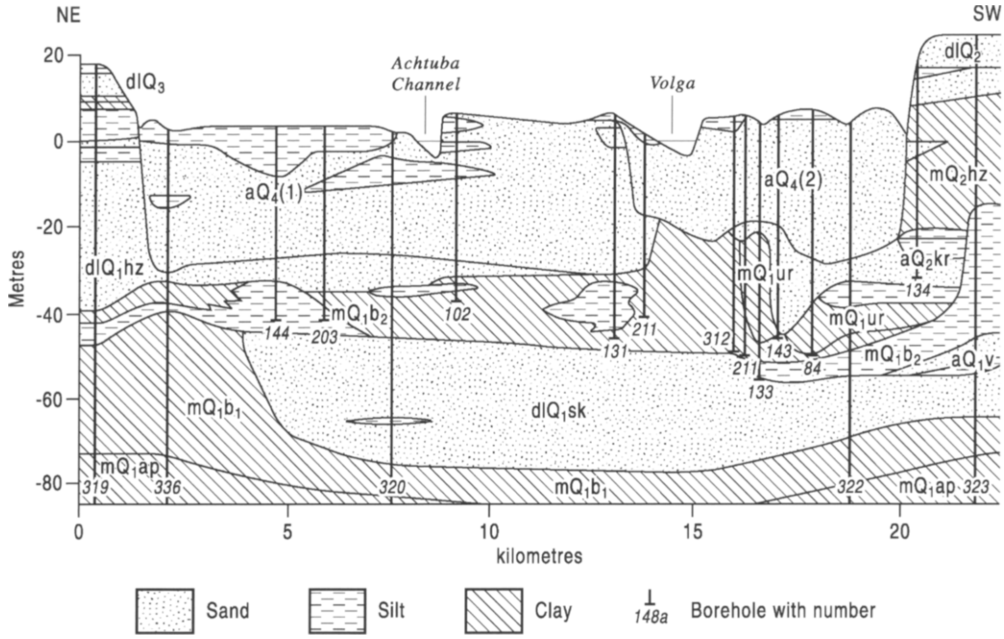


Fig. 14. Cross-section through the sediments of the Lower Volga near Yenotaevka (after Goretskiy (1966) with modifications). See Figure 1 for location. Sediments are identified using the same notation as in Figures 12b and 13. Environment codes are: a, fluvial; m, marine (i.e. Caspian); dl, deltaic. Age codes are: Q_1, Lower Pleistocene; Q_2, Middle Pleistocene; Q_3, Upper Pleistocene; Q_4, Holocene. Name codes (Fig. 2) are: ap, Apsheron Series; b_1, Lower Baku Suite; sk, (?) Solikamsk Suite; b_2, Upper Baku Suite; v, Venedy Series; ur, Urundzhik Suite; kr, Krivichi Series; hz, Khazar Series; (1), Floodplain Lower Suite; (2), Floodplain Upper Suite. Notes: (1) The Urundzhik Suite (mQ_1ur) is equivalent to the Upper Baku Suite according to Vasiliev (1986). However, Vasiliev (1986) did not identify the Urundzhik Suite within the Lower Volga area. (2) The Krivichi Series (aQ_2kr) is equivalent to the estuarine-lacustrine Singil Suite (Fig. 2) according to Vasiliev (1986). (3) The thick sand unit labelled dlQ_1sk is both significant and controversial. It was originally described by Goretskiy (1966) as of fluvial (deltaic) origin and assigned to the Solikamsk Suite, although no sedimentological proof of this depositional environment was provided. In contrast, Vasiliev (1980) regarded this deposit as a part of the (Caspian marine) Baku Suite. According toVasiliev (1980, 1986) the real position of the Solikamsk Suite in the Lower Volga is above the Baku deposits and this point of view has formed the basis for this part of the correlation table (Fig. 2). The present authors, indeed, consider that these sands could be offshore (beach) deposits. In the Middle Volga (Fig. 13), deposition of the Solikamsk Suite marks the end of a major phase of incision and the start of the subsequent phase of aggradation. The observed relationship between this incision and the Solikamsk Suite, and the suggested relationship between the Solikamsk Suite and the Baku Suite, suggest that this incision phase occupied the late Early Pleistocene and/or the earliest Middle Pleistocene.

(Matoshko *et al.*, 2002). These have been well researched palaeontologically and radiocarbon dated (Gozhik & Novoselsky, 1989) and, thus, enable detailed subdivision of alluvial deposits within the lower reaches of rivers, estuaries and on the shelf. Index beds of red and brown waste mantles and corresponding buried soils overlie the pre-Quaternary and, in part, Lower Pleistocene alluvial suites in the basins of the Dniester (Fig. 4), Dnieper (Figs 8, 9) and Don (Fig. 11), separating them from younger alluvium. Till of the Don glacial complex serves as a regional index bed for the Don–Oka Lowland. It is attributed to the early Middle Pleistocene on the basis of mammalian faunas from overlying and underlying deposits, both of which include *Mimomys savini* (Holmovoi *et al.*, 1985; Turner, 1996). Deposits of the Dnieper glaciation (Saalian; OIS 8) occur in the Middle Dnieper (Figs 8, 9) and Upper Volga (Matoshko & Chugunny, 1993), fixing the upper boundary of the Krivichi Series in both river systems. The younger alluvial suites are incised into this glacial complex or overlie it. The upper stratigraphical boundaries of individual alluvial suites are defined in key sections by overlying buried soils within loess/slope-wash complexes (Veklich & Sirenko, 1976).

Biostratigraphy

The fluvial deposits in the study region contain various types of fossils, including mammals, molluscs, spores, pollen, plant macrofossils and ostracods. Most types serve for palaeogeographical and palaeoecological reconstruction; it has been established that mammal remains have the greatest biostratigraphic importance. It is, however, important to be aware that fluvial deposits typically contain reworked fossils, often giving rise to mixed assemblages.

The data on mammal faunas from fluvial deposits are summarized in numerous works (Gromov, 1948; Goretskiy, 1966, 1970, 1982; Alexeeva, 1977; Iossifova, 1977; Markova, 1982, 1998; Krasnenkov *et al.*, 1984; Rodzyanko, 1984; Holmovoi *et al.*, 1985; Adamenko *et al.*, 1986; Bilinkis, 1992; Michailesku & Markova, 1992; Iossifova & Krasnenkov, 1994; Rekovets, 1994; Iossifova, 2001; Agadjanian, 2002; Matoshko *et al.*, 2002). Evidence from molluscs (Goretskiy, 1966, 1970, 1982; Tchepalyga, 1967; Krasnenkov *et al.*, 1984; Bludorova & Fomicheva, 1985; Holmovoi *et al.*, 1985; Gozhik & Novoselsky, 1989; Gozhik, 1992; Michailesku & Markova, 1992) is a further important biostratigraphic tool. Mammalian and molluscan fossils have been found together at many sites. Molluscs have been especially effective for establishing the stratigraphical sequence and for the correlation of alluvial and marine-liman deposits in the lowermost reaches of rivers.

Mammalian and molluscan biostratigraphic evidence is summarized in Figures 4, 8, 10–12. The allocation of fluvial mammalian assemblages to the main mammal faunal complexes of the Pliocene–Quaternary (Fig. 2) follows Gromov (1948). Each complex is characterized by a unique combination of taxa in each faunal province, differing from older and younger ones as a result of evolution and extinctions (Vangeingeim, 1982). The freshwater mollusc complexes defined by Tchepalyga (1967) reflect both evolutionary changes and migrations in response to climatic oscillations.

Biostratigraphic evidence does not occur uniformly in the deposits of the rivers under consideration. Most of the suites of the Middle and Lower Dniester are well studied; indeed, the Middle–Lower Dniester can be regarded as a key area for the correlation of fluvial suites on the basis of mammalian and molluscan faunas. The Upper Pleistocene and Lower Pleistocene deposits of the Upper Don are also an important source of systematic data from small mammal faunas. Several Lower and Middle Pleistocene suites of the Lower and Middle Dnieper also include fossiliferous deposits. However, insufficient information is available for many suites, in particular on mammalian and molluscan faunas from many of the Miocene and Pliocene deposits of the Dnieper and Volga.

In the Dniester, isolated discoveries of a *Hipparion* mammal fauna occur in the Balta Series of the Upper Miocene. Richer faunal assemblages are associated with the Lower Pliocene Stolnichen Series; the mammals include *Dicerorhinus* aff. *megarhinus* De Christol, *Antilope* sp., *Hipparion* sp., *Gazella* cf. *borbonica* Deperet et Bravard, *G. deperdita* (Gervais), *Homotherium* cf. *crenatidens* Fabrini. However, these species are insufficient to characterize any specific mammal biozone, although it is presumed that the Stolnichen Series falls within the early part of the time span of the Moldova fauna (Fig. 2). The mollusc most characteristic of this series is *Plicatibaphia* cf. *wetzleri* Dunker. Palynological data reveal a subtropical climate during the accumulation of the Stolnichen Series.

The younger Kuchurgan Suite contains mammal remains (*Mastodon borsoni* Hays, *Hipparion gracile* Kaup, *Dicerorhinus megarhinus* De Christol, *Promimomys moldavicus* Kormos, *Pliomys kowalskii* Schevtschenko, etc.) that are identical to those from the Karboliya Beds, which are the stratigraphical equivalent of the Kuchurgan Suite in the area west of the Dniester (Hubka, 1982) and which provide the basis for distinguishing the Moldova faunal complex of the Lower Pliocene. Molluscs such as *Plicatibaphia flabellatiformis* (Grigorovich-Berezovski), *Psilunio bogatschevi* (Grigorovich-Berezovski), *P. haneri* (Horn), *P. stolizkai* (Neumayer) and *Rugunio lenticularis* Sabba are common in the Kuchurgan Suite and Karboliya Beds, as well as the subsequent Runkashiv Suite (Fig. 2).

The following molluscs have been established in the Sokol Suite of the Kinel' series of the Kama tributary of the Middle Volga: *Viviparus dresseli* Tournouer, *V. mangikiani* Bogatschev, *V. achatinoides glogovensis* (Stefanescu), *Valvata vanciana* Tournouer, *V. piscinalis* (Müller), *Borysthenia naticina* (Menke), *Bithynia spoliata* Stefanescu, *B. vukotinovici* Brusina, *Lithoglyphus rumanus* Stefanescu, *Unio* ex gr. *rumanus* Fontannes, *Potomida sibinensis* (Penecke) and *Psilunio serratoradiatus* (Bogatschev). Based on the presence of Levantine (Late Pleistocene of Romania; i.e. Romanian) unionides and some gastropods of the Kuyalnik type, the Sokol Suite has been correlated (e.g. by Goretskiy, 1964) with the Lower Levantine stage, the Lower Kuyalnyk and lower Middle Akchagyl (i.e. the early Late Pliocene; Fig. 2). The present authors correlate the Sokol Suite with the Runkashiv Suite of the Dniester using both magnetostratigraphy (indicating the Gauss chron) and biostratigraphy, and tentatively estimate their age as *c.* 3 Ma (Fig. 2). The Runkashiv Suite of the Dniester can probably be correlated with this Sokol Suite, which also has *Amphimelania impressa* Bogatschev, *Valvata uralica* G. Popov, *Viviparus mangikiani* Bogatschev and *Bithynia vucotinovici* Brusina.

Molluscs from the Vadul-lui-Vode Suite include *Pristinunio davalai* (Porumbaru), *P. procumbens* (Fuchs), along with mammals such as *Elephas planifrons* Falconer, *Archidiskodon* (*Mammuthus*) *meridionalis meridionalis* (Nesti) and *Equus stenonis* Cocchi. This Dniester suite is correlated with the Uryv Series of the Upper Don, on the basis of small mammals, and with the Khapry Suite of the Lower Don. The Khapry Suite is the context for the mammal complex of the same name, characterized by *Archidiskodon gromovi* Garutt et Alexeeva, *A. meridionalis meridionalis* (Nesti), *Equus robustus* Pomel, *Dicerorhinus etruscus* (Falconer) and *Elasmotherium caucasicum* Borrissiak. The fossils from the Rashkiv Suite of the Dniester are also representative of the Khapry mammal complex and include typical molluscs of the Late Akchagyl Stage: *Bogatschevia tamanensis* (Ebersin), *B. bugasicus* (Ebersin) and *Potomida* (*Wenzinella*) *moldavica* Tchepalyga. It is probable that the small mammal remains from the Belaya Gora Suite of the Upper Don, represented only by the rhizodont voles (Holmovoi *et al.*, 1985), correlate with the fauna from the Rashkiv suite.

Although not itself a fluvial deposit, the Shirokino Unit (red and reddish-brown clays, overlying the fluvial Pyryatin and Parafiivka Series of the Dnieper; Fig. 8), has yielded a mammal fauna (Matsui *et al.*, 1993). This consists of the lagomorph *Ochotona* sp. and the rodents *Citellus* sp., *Plioscirtopoda* sp., *Pliomys kowalskii* Schevtschenko, *Mimomys* sp., *M. reidi* Hinton, *Villanyia petenyii* (Mehely) and *V. fejervaryi* Kormos; the *Villanyia* group of voles predominates. This fauna was obtained from six boreholes in the Orel River basin, *c.* 150 km SE of Vyazivok (Fig. 1). This characteristic Villanyian (i.e. Khapry) fauna provides the basis for dating these particular reddish deposits to the Late Pliocene and for correlating them with the Kuyalnyk marine deposits of the Black Sea (Fig. 2). The present authors consider that both this Shirokino Unit and the fluvial Chornobyl Series formed during long and overlapping spans of time: the latest Miocene to Early Pleistocene and late Early Plicoene to latest Pliocene, respectively (Fig. 2), although the Chornobyl Series is not directly dated.

The Lower Pleistocene Boshernitsa Suite of the Dniester contains the younger Taman mammalian faunal complex and molluscs such as *Bogatschevia sturi* M. Hörnes, *B. Unio sturi* var. *rodzjankovi* Bogatschev and *Margaritifera arca* Tchepalyga. It is correlated with the middle suite of the Goryanka Series of the Upper Don, which is characterized by small mammals (e.g. *Mimomys* ex. gr. *pusillus* Mehely, *M. intermedius* Newton (= *Mimomys savini* of western authors) and *Allophaiomys pliocaenicus* Kormos) of the same faunal complex (Holmovoi *et al.*, 1985). Molluscs such as *Unio sturi* var. *caudata* Bogatschev, *Unio sturi* var. *scutum* Bogatschev, *Unio* (*Eolymnium*) *pseudochasaricus* Tchepalyga and *Corbicula apsheronica* Andrussov, together with mammals of the late Taman complex, with *Archidiskodon meridionalis tamanensis* Dubrovo, characterize the Kisnytsia Series of the Dniester. Faunal remains from the Kairy Series of the Lower Dnieper are also assigned to the Taman complex. Palynologically, the fluvial record shows a decline in temperature at the end of the Early Pleistocene.

According to Markova (1998, p. 323), the most advanced Early Pleistocene faunas are characterized by the occurrence of *Microtus* (*Pallasiinus*) ex gr. *oeconomus* (Pallas). These faunas were named after Petropavlovka in the Upper Don (Fig. 10), described at first by Krasnenkov & Agadjanian (1975) and Alexandrova (1976). The Petropavlovka fauna is defined by the steppe lemmings *Prolagurus pannonicus* Kormos and *Eolagurus argyropuloi* I. Gromov et Parfenova, and the vole *Microtus* (*Stenocranius*) *hintoni* (Kretzoi) (Markova, 1998). A small mammal fauna of similar evolutionary level has also been found in the lower Dnieper near Karai Dubina village (Fig. 1) (Markova, 1982). These faunas are also typified by the rhizodont voles *Mimomys savini* Hinton and *M. pusillus* Mehely, as well as a late species of the genus *Borsodia*. However, according to Rekovets (1994) the Karai Dubina fauna is discerned by domination of *Microtus* (*Stenocranius*) ex gr. *hintoni-gregaloides*, the presence of *M.* (*Pallasiinus*) *protoeconomus* Rekovets and appearance of the *Prolagurus pannonicus transylvanicus* Terzea. Such species as *Mimomys savini* Hinton and the genus *Borsodia* are, indeed, absent in the Rekovets list. Rekovets (1994) thus concluded that this assemblage correlates to the fauna of the Mihailovka Suite (Dniester) and so is rather older than the Petropavlovka fauna. Palaeomagnetic studies have indicated that the beds with this fauna belong to the upper part of the Matuyama reversed polarity Epoch. In the Karai Dubina section reversed palaeomagnetism has been recorded from floodplain alluvial deposits, which overlie the channel facies deposits with the small mammal remains (Velichko *et al.*, 1983). The rich fauna from this Karai Dubina Suite comprises *Apodemus sylvaticus* Linnaeus, *A. flavicollis* Melchior, *Allocricetus bursae* Schaub, *Cricetus praeglacialis* Schaub, *Clethrionomys glareolus* Schreber, *Prolagurus pannonicus transylvanicus* Terzea, *Eolagurus argyropuloi* I. Gromov et Parfenova, *Mimomys pusillus* Mehely, *Microtus* (*Stenocranius*) ex gr. *hintoni-gregaloides*, *M.* (*Pallasiinus*) *protoeconomus* Rekovets, and *Microtus* cf. *arvalinus* Hinton and others (e.g. Matoshko *et al.*, 2002; Rekovets, 1994). The stratigraphical position and biozone represented at these key sites have been widely debated. Suggestions include: that the Petropavlovka Suite marks a distinctive biostratigraphic substage (Alexandrova, 1976); that it marks the start of the Tiraspol biozone (Holmovoi *et al.*, 1985; Rekovets, 1994); that both suites mark the end of the earlier Taman biozone (Markova, 1998); and that the Petropavlovka Suite represents OIS 20 (Iossifova, 2001). Like Matoshko *et al.* (2002), the present authors favour the view that it marks a transitional position between the Taman and Tiraspol biozones (Fig. 2).

Returning to the Dniester, the Middle Pleistocene alluvium of the Koshnitsa and Kolkotov suites contains the mammal fauna of the Tiraspol complex, including *Mammuthus trogontherii wusti* M. Pawlow, *Alces latifrons* (Johnson), *Cervus acoronatus* Beninde, *Equus* aff. *sussenbornensis* Wusti, *Lagurus transiens* Janossy, *Microtus* (*Stenocranius*) *hintoni* (Kretzoi) and *Mimomys intermedius* Newton. Molluscs of the Koshnitsa Suite are similar to the modern complex, whereas many molluscs of the Kolkotov Suite represent the subtropical zone, such as *Potomida littoralis* Cuvier, *P. kinkelini* (Haas), *Viviparus tiraspolitanus* Pavlov and *V. kagarliticus* Lungershausen. The Koshnitsa Suite correlates with Traktemyriv Suite of the Middle Dnieper, which contains *Unio pseudochasaricus* Tchepalyga and *Crassiana pseudolitoralis* (Clessin). The biostratigraphical correlation of the Kolkotov Suite with the Nikopol Suite of the Lower Dnieper (Fig. 2), the Muchkap Suite of the Upper Don and the Venedy Series of the Middle Volga is also well established. Remains from the younger Kryvichi Series (Dnieper and Volga), Strelitsa Suite (Upper Don) and Varnitsa Suite (Dniester) are attributed to the Singil mammal complex. This follows the *Mimomys–Arvicola* transition recognized throughout Europe (Turner, 1996); in the Middle Dnieper it is characterized by *Arvicola chosaricus* Alexandrova, *Arvicola mosbachensis* Schmidtgen, *Eolagurus luteus* Eversmann, *Microtus* (*Stenocranius*) *gregalis* Pallas, *Microtus arvalis* (Pallas), *M. oeconomus* Pallas, *Cricetus praeglacialis* (Schaub) and *Lagurus lagurus* (Pallas). In the Upper Don this transition seems to occur between the Muchkap and Tafino suites: the Muchkap Suite contains *Mimomys* but the Tafino Suite contains *Arvicola* (Iossifova, 1977; Turner, 1996). This mammal complex is named after the Singil Suite of the Caspian basin, which represents a relatively minor transgression of the Caspian Sea, associated with the development of estuarine deposits near its present northern margin (downstream of the Lower Volga cross-section line shown in Fig. 1). The representatives of the Upper Palaeolithic faunal complex include *Coelodonta antiquitatis* Blumenbach, *Megaloceros giganteus ruffi* (Nehring), *Cervus elaphus* Linnaeus, *Capreolus capreolus* Linnaeus, *Rangifer tarandus* Linnaeus, *Bison priscus* Bojanus and *Mammuthus primigenius* Blumenbach; this complex is characteristic of the 3rd, 2nd and 1st Terrace suites but is especially common in the basal alluvium of the Modern Suite of the Middle Dnieper, along with remains of the modern fauna.

Magnetostratigraphy and other dating

Palaeomagnetic investigations have been carried out on alluvial sections in the Lower and Middle Dniester (Bukatchuk *et al.*, 1983), the Upper Don (Holmovoi *et al.*, 1985) and the Middle Volga (Bludorova & Fomicheva, 1985). They have allowed correlation of local stratigraphical schemes with the International Scheme for the Miocene–Pliocene and Quaternary (Figs 2, 4, 8–12).

Magnetostratigraphy is of particular importance for correlation between fluvial and other environments. An example is provided by the Domashka Suite of the Middle Volga (Fig. 2), represented by estuarine/fluvial sands and clays, which corresponds to the Domashkinskie Vershiny deposits of Alexandrova *et al.* (1977). These deposits, containing freshwater molluscs and remains of *Mimomys intermedius*, rest upon the 'marine' (Caspian) Akchagyl deposits with their characteristic salt-water molluscan fauna. Alexandrova *et al.* (1977) deduced that these freshwater sands and clays were deposited, following the post-Akchagyl regression, in the Early Apsheron Stage. They also determined reversed geomagnetic polarities in this deposit as well as in most of the Akchagyl deposits, indicative of the Matuyama chron, and found normal polarities (Gauss) in the deposits underlying the Akchagyl ones. Subsequently, marine molluscs of Akchagyl age (absent in Apsheron horizons) were found in this suite (Danukalova, 1996; Danukalova & Yakovlev, 1998; Yachemovitch *et al.*, 1998, 2000), leading Shick *et al.* (2002) to place it in the latest Akchagyl Stage, after the peak of the Akchagyl transgression but before the start of the Apsheron Stage. The geomagnetic polarities may well, thus, indicate the early Matuyama chron, before the Olduvai subchron, in which case the Domashka Suite of the Middle Volga could correlate with the Rashkiv Suite of the Dniester and the Belaya Gora Suite of the Upper Don. The present authors currently favour this latest Akchagyl age interpretation, although the alternative Early Apsheron interpretation is illustrated in Fig. 2.

At Vyazivok, on the Dnieper (Figs 1, 8), Vigilyanskaya (2001) reported reversed geomagnetic polarities in the Kryzhanivka Unit, which is regarded by the present authors as overbank deposits immediately post-dating the deposition of the Pyryatin Series, and in the overlying Shirokino Unit; the overlying loess/palaeosol complex has a normal polarity. Vigilyanskaya attributed this polarity reversal as indicating the Matuyama–Brunhes boundary, but the present authors consider that the Pyryatin Series is Late Miocene (Fig. 2), in which case the reversed polarities in the Kryzhanivka Unit would have to indicate an earlier reversed chron, presumably C3r (Fig. 2). Matsui *et al.* (1993) found, in reddish-brown and brown clays (presumed equivalent to the Shirokino Unit) and overlying loams, mammals indicative of the Late Pliocene to Early Pleistocene Khapry and Taman biozones. Thus, the reversed polarity in the Shirokino Unit probably represents the Matuyama. This reddish waste mantle deposit, found in the Dniester, Dnieper and Don basins, accumulated from the middle Meotian in the Upper Don basin (cf. Iossifova, 1977) and from the end of the Pontian in the Middle Dnieper basin (cf. Matoshko *et al.*, 2002) to the end of the Early Pleistocene. It consists of two main members; first, distinctive reddish or reddish-brown clay that covers all fluvial deposits starting with the Rashkiv Suite of the Dniester, the Goryanka Suite of the Don and the Chornobyl Series and older deposits of the Dnieper. There may, thus, be some variations in its upper age boundary between these river basins (cf. Fig. 2). In the Middle Dnieper the thickness of this first member is progressively reduced and its structure becomes less complex, the younger the fluvial deposit it covers (Matoshko, unpublished). The second member, a brown or reddish-brown silt, occurs mainly south of 48–49°N but has been recorded relatively rarely.

Reliable absolute dates from the fluvial deposits are rare. Radiocarbon dates (12.7–11.2 ka) have been obtained from the Neo-Euxinian mud of the Black Sea

(Gozhik & Novoselsky, 1989), separating the Ant Suite from the Modern Suite in the lower Dnieper. In the valley of the Upper Don, the age of the 1st and 2nd Terrace series is established to be in the range of 32–18 ka by the same method (Praslov, 1985). Radiocarbon dating of two members of the Floodplain Series in the Lower Dniester has also fixed the initial accumulation of the lower member at *c.* 15 ka (Bilinkis, 1992).

6. FLUVIAL DEVELOPMENT DURING THE LATE CENOZOIC

Erosion–accumulation cycles

The fluvial record in the study region begins with the marine regression at the end of the Palaeogene. The first reliable evidence for the existence of the river systems of the Carpathian piedmont dates from the Early Miocene (Bilinkis, 1992), but subsequently marine conditions were re-established and persisted until the end of the Miocene. Valley incision began in the Late Miocene and has reached net figures (measured with respect to modern surface altitude) of 160–200 m in the middle reaches of the Dnieper, Don and Volga and 250–270 m within the Dniester left bank area, where incision has been continuous. Several important erosion–accumulation cycles were established during this interval.

The oldest cycle is represented by the filling of the Palaeo-Don valley (Fig. 1) with Middle Miocene deposits (Iossifova, 1977). Renewed incision in the Don system continued to the end of the Pliocene, forming a staircase of terraces (Fomenkovo Suite to Belaya Gora Suite – Fig. 11). This was followed by a period of general accumulation up to the early Middle Pleistocene Don Suite, which corresponds to the Don glaciation. Renewed accumulation after the Don Glaciation finished at the end of the Middle Pleistocene with the start of the most recent incision phase, which was followed by the formation of a new terrace staircase (4th terrace to floodplain terrace; Fig. 11).

In the Middle Volga the oldest incision occurred in the Pliocene. It was filled first by the Kinel Series (Sheshma, Chelny, Sokol and Chistopol suites), which was overlapped, following the Akchagyl Caspian marine phase, by Lower and Middle Pleistocene alluvium (Figs 12, 13). Renewed incision began in the Volga valley at the beginning of the Middle Pleistocene, following which the Solikamsk Suite was emplaced over 60 m below modern river level (Fig. 13). Subsequent accumulation of several thick suites (Lower, Middle and Upper Venedy suites, the Lower and Upper Krivichy suites, the Lower and Upper Zhiguli suites and the Periglacial or 3rd Terrace Suite) nearly reached the maximum level of the previous accumulative phase (Fig. 13). This was followed by the most recent phase of erosion, which has cut down approximately 60 m from the late Middle Pleistocene level in the vicinity of the Zhiguli upland (Fig. 13).

In the Middle Dnieper it appears that the first phase of major incision was in the Late Miocene, following the deposition of the Shostka Series and before the aggradation of the Pyryatin Series, which only partly filled the incision before renewed erosion occurred at the end of the Pontian (Figs 2, 8, 9). During the early Pliocene this erosion was infilled and buried by the Parafiivka Series (Figs 8, 9). Subsequent cut-and-fill sequences (Chornobyl Series to Modern Suite) show little net incision or accumulation from the Pliocene to the present day (Figs 2, 8, 9). Overall the valleys were infilled in the Middle Pleistocene by the thick (up to 50 m) Krivichy Series before the Dnieper Glaciation, then the Hnidyn Suite (up to 70 m thick) immediately after this glaciation, before the subsequent 60–80 m of incision, making approximately 40 m of net infill.

The development of valleys in the Carpathian piedmont, such as the Dniester, was significantly different. The first erosion–accumulation cycle was in the Late Miocene–Early Pliocene. It is marked by the alluvium of the Balta and Stolnichen series (Fig. 4). There followed progressive but pulsed incision, perhaps triggered by climatic fluctuation, interspersed with short phases of accumulation, continuing through the Pliocene and Quaternary. This gave rise to the terrace staircase illustrated in Figures 4, 6 and 7. Acceleration of incision occurred at the beginning of the Pleistocene and brought about the separation of the Dniester, Prut and Siret rivers from the former single Carpathian Foreland river (Bilinkis, 1992).

After marine regressions and deglaciation phases (see below), new drainage configurations appeared, but these generally inherited the main depressions of the previous fluvial cycles. Major drainage reorganizations took place at the ends of depositional phases. This occurred at the beginning of the Middle Pleistocene in the Middle Volga and during the Early Pliocene in the Middle Dnieper.

Transport and sedimentation

The characteristics, described above, of the fluvial deposits in the study region show that processes of erosion and sediment transport have remained essentially unchanged during the Late Cenozoic. During incision phases most debris was transported along the valleys and deposited in the inland basins that were precursors of the present Caspian Sea, Sea of Azov and Black Sea, although small volumes of sand and coarse material accumulated in the valleys. During aggradational phases there was predominant accumulation in the valleys and a general decrease in grain size. At such times the environment of deposition could fluctuate variously between fluvial, limnic, deltaic/estuarine and marine conditions. Goretskiy (1966) explained the unusual predominance of the channel facies of most Volga suites, where this river crosses the Zhiguli Upland (Fig. 13), as a result of repeated lateral erosion of the overbank and abandoned channel facies in the narrow valley, even when conditions generally favoured aggradation elsewhere.

Two main types of alluvial accumulation can be distinguished in plan. First, the oldest cycles (Balta Series, Stolnichen Series and Kuchurgan Suite) in the development of the Carpathian rivers show a 'sheet' distribution, as, presumably, do the Yergeni sands. The second type is an even spread of alluvial deposits down valley. This type is complicated by regional heterogeneity of geological structure, which resulted in vast basins of predominant accumulation, canyons (original conduits of fluvial transportation) and internal fans. The main development of deltas took place at times of stabilized or increased fluvial sedimentation and of favourable conditions on the adjoining shelf.

Mineral composition of the sediments of the East European Platform rivers reflects erosion of mostly Mesozoic–Cenozoic sedimentary bedrock. Within the Dnieper basin the predominant sources are, instead, waste mantles of the Precambrian igneous and metamorphic rocks of the Ukrainian Shield. There is no overall trend in particle size distribution across all the rivers. There is noticeable downstream fining in the Volga sediments, whereas channel facies of the Dniester remain coarse downstream to the river mouth. The Upper Pleistocene–Holocene suites of the Lower Dnieper, on the other hand, are coarser than those of the Middle Dnieper.

There is a clear influence of glaciation on the mineral assemblages and petrographic composition of Quaternary depoits of the Dnieper, Don and Volga, expressed by increases of northern erratic components. Erratics first appear in the Laishevo Suite of the Volga (Fig. 12) and the Goryanka Series of the Upper Don (Fig. 11), in the early part of the Early Pleistocene. Although the occurrence of erratic pebbles and boulders is mostly restricted to the immediate area of glaciation, large erratics were sometimes ice-rafted downstream and glacial influence can be traced over great distances from the mineral composition of channel sands. Fluvial scour of glacial deposits led to the concentration of coarse material in the basal subfacies of the suites laid down following glaciations. Once introduced, glacial indicator materials were reworked both downstream and into younger fluvial sediments.

7. DISCUSSION

The rivers under consideration have been central to a long-standing debate about the role and relationship of tectonic and climatic factors in terrace formation and in the evolution of fluvial processes in general; the authors now wish to set forth their own point of view.

Neotectonic movements

Tectonic structure and neotectonic uplift from the Middle/Late Miocene onward have controlled fluvial processes in these river valleys. This uplift was spatially heterogeneous and pulsed (Lukina *et al.*, 1985; Bilinkis, 1992; Palienko, 1992) and, in the opinion of the present authors, alternated with phases of stabilization and subsidence. It is a reflection of a complex combination of different crustal movements: oscillatory movements of the basement and folding of the sedimentary cover, subduction beneath the Carpathian orogenic belt and opposite overfolding and thrusting within the foreland. There has been a westward increase in neotectonic uplift from the western margin of the East European Platform into the transition zone bordering the Carpathian Orogenic Belt (Bilinkis, 1992). Uplift rates also increase eastward across the transition zone between the East European Platform and the Urals (a Hercynian orogenic belt) (Sidnev, 1984).

The authors consider erosion–accumulation cycles to be responses to alternations between uplift and relative stability. Processes such as channel incision or valley aggradation occur when the regional or local base level changes. A comparison of the longitudinal profiles of the Dniester (Fig. 5), Volga and Dnieper (Goretskiy, 1966; Matoshko *et al.*, 2002) shows concordant changes in each valley. Three mechanisms for base-level change can be suggested: sea-level oscillations, lateral variations in vertical motions at the platform margin and differential movements within the platform. Bilinkis (1992) interpreted the river terrace staircases of the Dniester and Prut as the result of uplift pulses, the frequency of which progressively increased from the Pliocene to the Holocene, although their duration progressively decreased over the same timespan.

Oscillatory or uniform uplift in the Carpathian piedmont area resulted in the formation of narrow terraces (the Upper Pliocene to Holocene terraces of the Dniester, Prut and Siret; Fig. 1). Wide terraces separated by low scarps are attributed to moderate uplift. The latter situation has given rise to the fluvial relief of the Middle/Upper Pleistocene to Holocene of the platform rivers (Dnieper, Don and Volga) and may also have prevailed in the Carpathian piedmont area in the Late Miocene to Early Pliocene. Stabilization of movements led to the formation of more gentle longitudinal channel profiles and wide alluvial plains. Such plains developed in the Middle Dnieper in the Late Miocene and in the Middle Pleistocene, before the Dnieper Glaciation. Subsidence of the region was accompanied by valley infill of continental and marine deposits. The origin of thick lacustrine strata within fluvial sequences such as the Kinel Series of the Volga and the Krivichi Series of the Middle Dnieper can be explained by localized subsidence relative to regional base level.

It is supposed that variations in crustal movements within different tectonic structures has caused the cycles of erosion–accumulation in the different rivers to be out of phase. Crustal movements have controlled changes of drainage pattern and have determined local areas of predominant aggradation or scour. Up to 9000 m of Miocene to Pliocene continental deposits, including fluvial strata, accumulated in the western part of the Carpathian Foreland (the Odobesht depression; Bilinkis, 1992). The predominant influences on the development of the Middle Dnieper valley were the different tectonic regimes of the Ukrainian Shield and the Dnieper–Donets Aulacogen. At the point where the Dnieper crosses the Shield there is a prominent break of slope in the modern longitudinal profile and a corresponding break in most of the Dnieper fluvial suites. The valley becomes narrower in the Ukrainian Shield and the levels of beds within different suites converge as they approach it. Therefore, this region is considered as the base level of erosion for the Upper–Middle Dnieper and its tributaries (Matoshko *et al.*, 2002). In the Middle Dnieper sedimentary basin (Fig. 1), variations between uplift and crustal stability, and even subsidence, have led to differences in the fluvial records compared with the aforementioned evidence from the Shield (Matoshko *et al.*, 2002). This basin, located at the transition between the Ukrainian Shield and the aulacogen, has experienced predominant fluvial sedimentation (Matoshko, 1996). In contrast, the smooth longitudinal profile of the Solikamsk Suite of the Volga (Obedientova, 1977) shows the absence, at the beginning of the Middle Pleistocene, of differential tectonic movements on any structures crossed by the Volga, regardless of their geometry. There is a significant tilting of the Lower Pleistocene Kairy Series (Lower Dnieper) and Kisnytsya Series (Lower Dniester) towards the Black Sea Depression.

Sharp changes of suite thickness, bed deformation, abnormal local narrowing and widening of valleys, changes in their orientation, surface relief and channel deformation can all be explained by differential tectonic movements related to local structures. These were most intensive within the transition zone between the East European Platform and the Carpathian Orogenic Belt, where block movements, thrusts and folds deformed sediments (Bilinkis, 1992). The vertical displacement of the Lower Pliocene alluvium reaches 250 m on the right bank of the Dniester and increases towards the Carpathians. Minor deformation is seen in most Pleistocene Dniester alluvial suites. Similar movements within the platform had a less significant effect (Volkov & Sokolovskiy, 1976; Palienko, 1992). The widest parts of the Volga valley coincide with zones of Quaternary subsidence (the Kostroma and Sura–Vetluga troughs and the Melekes Depression; Obedientova, 1977). There is a localized canyon-like narrowing where the Volga crosses the Vyatka Dislocation zone (between Kazan and the confluence between the Volga and the Kama; Fig. 1). The tectonic regime of the Western Fore-Caspian Trough controlled the development of the Lower Volga in the Pliocene to Quaternary (Kopp & Tveritinova, 2001).

Climate

At the beginning of the paper (section 2) a scheme envisaging climatic control of terrace formation (Veklich & Dubniak, 1975) was considered. In an alternative scheme (Pokatilov & Bukatchuk, 1989), the lower parts of alluvial strata and corresponding soils formed under warm-climate conditions and tectonic stability, the upper part of alluvial strata and corresponding loess horizons under cold-climate conditions. In the authors' opinion, these and other similar schemes are simplistic; although a climatostratigraphic approach is well established by studies of glacial and non-glacial deposits at high and middle latitudes, atmospheric composition (from ice cores), oceanic sedimentation, evolution of soils, palaeoecology, recognition of past climates in fluvial sequences can be problematic.

Indications of temporal coincidence between river terrace formation and climatic events recorded in deep-sea sediments and ice cores are not proof of Milankovitch climatic forcing. To demonstrate the latter would require analysis of the relationship between climatic oscillations (oxygen isotope stages), oscillations of precipitation and humidity and fluctuations of key fluvial parameters (such as runoff, regime, discharge, suspended load and bed load). The geographical location in relation to climatic zones and Pleistocene ice sheets would also have to be considered. So, too, would hydrological calculations based on observations of modern river processes, which control changes in channel width and depth, erosion rates and sediment transport, as well as the channel regime.

From the Late Miocene to the Holocene, the climate in the study region changed from subtropical to subarctic. In any case, the major rivers flowing north to south each crossed several climatic zones. It can be assumed that differences in thicknesses of suites and facies, as well as lithological characteristics of fluvial sediments, have been controlled by some or all of the above-mentioned factors. According to Lavrushin (1966), the general scheme of alluvium structure (cf. Shantser, 1951) persists across different climatic zones, but the ratio between its main facies and their diagenetic features varies significantly. In this context, 'diagenetic features' means a wide range of cryogenic structures, desiccation cracks, of hydromorphic soil horizons, secondary organic matter content (associated with soils), and authigenic minerals, especially carbonates, iron and manganese hydrates, salts, hydromicas and vivianite. All these give a specific appearance to alluvial facies and change primary fluvial sedimentary structures to different extents.

The issue of fluvial sedimentation during glaciations deserves attention, however, particularly since the Volga, Dnieper and Don basins experienced three or four Pleistocene glaciations and a small part of the Upper Dniester was glaciated on a single occasion (Fig. 1). As already noted, continental ice sheets created a new sediment source for fluvial reaches within their influence, while sources elsewhere remained unchanged, allowing glacial inputs to be recognized from analyses of appropriate fluvial sediments.

The 'periglacial' suites have been attributed to direct glacial influence by some investigators (Goretskiy, 1966, 1970; Obedientova, 1977; Matoshko & Chugunny, 1993). Goretskiy attributed their lithofacies to glacially-fed rivers, carrying increased proportions of fine-grained material. In contrast, Lavrushin (1966) recognized such deposits as typical of conditions in the subarctic zone and not necessarily associated with ice sheets. However, this view cannot explain the unique occurrence of 'periglacial' suites in the Middle Dnieper and Upper Don. In the Dnieper, it is thought that most of these deposits formed at the end of the Dnieper Glaciation in canyons between blocks of dead ice in the axial zone of the Dnieper Ice Stream. After the glacial load was removed, this zone was locally uplifted in response to glacio-isostatic rebound (Matoshko & Chugunny, 1993).

According to Vasiliev (1980), the sandurs of the Dnieper (OIS 8), Moscow (OIS 6) and Valdai (OIS 2) glaciations continue downstream along the Volga valley as corresponding river terraces, including the periglacial suites mentioned above. In contrast, in the Middle Dnieper (right bank), valley sandur structure and its occurrence in the southwestern part of the Dnieper Ice Stream resemble fans elongated downstream and ending abruptly a few tens of kilometres from the limit of glaciation, without any connection with normal fluvial terraces. The thick meltwater-derived Shevchenko Suite, deposited in the Middle Dnieper during the Dnieper glaciation, occupies the glacially eroded Shevchenko Depression (Matoshko, 1995).

Significant fluvial changes at the transition from the Late Pleistocene to the Holocene are well known in Western and Central Europe. In the last decade the relics of so-called macromeanders have been found within the lower levels of the lowest terrace and within the floodplains of the 2nd- and 3rd-order rivers throughout a large area of the East European Plain, including much of the Dnieper, Volga and Don basins (Sidorchuk *et al.*, 2001). These macromeander channels can be 15 times wider than recent meanders of the same rivers. It is supposed that the major rivers adopted a braided regime at this time.

In the southern part of the East European Plain, radiocarbon dates of 12–14 ka have been obtained from fluvial deposits beneath macromeanders attributed to increased fluvial discharge in response to permafrost conditions in the periglacial zone of the Valdai glaciation (Sidorchuk *et al.*, 2001). The existence of this permafrost is confirmed by the discovery of ice-wedge casts in the upper horizons of the 1st Terrace Series in the Middle Dnieper and in the overbank alluvium of the same terrace in the Lower Prypyat (Bugai *et al.*, 2001; Matoshko *et al.*, 2002). These facts are evidence that, although the more durable and consistent climatic cycles have given rise to the structure of most alluvial suites, short-term catastrophic climatic events can sometimes significantly affect fluvial architecture.

Development of marine basins and its influence on fluvial processes

As already noted, the development of the Caspian Sea, Sea of Azov and Black Sea, as well as their precursors, is a complex problem. Attempts have been made to correlate fluvial and marine horizons and events for the Volga (Goretskiy, 1966; Obedientova, 1977), the Don (Goretskiy, 1982), the Dnieper (Goretskiy, 1970; Gozhik, 1982) and for the Danube and Prut (Michailesku & Markova, 1992). Nevertheless, there are very few facts linking episodes within the evolution of the marine basins and the rivers (Fig. 2).

These marine depressions have received huge amounts of terrigenous material, representing an archive of considerable potential, although yet to be studied. The earliest Cenozoic fluvial records coincide with the development of the Paratethys Sea and its subsequent division into several basins (Semenenko, 1993). In the Late Miocene (Pontian), deep incision affected the whole Dnieper basin, transforming its valleys into narrow and steep-sided canyons (Matoshko *et al.*, 2002). This incision can be associated with the fall in sea-level following the isolation of the Mediterranean and Black Sea basins in the Messinian, 6.5 Ma according to Semenenko (1993). The mouth of the Palaeo-Dnieper moved to the Black Sea continental slope and terrigenous material began to accumulate in the basin, as is confirmed by deep-water boreholes (Hsü & Giovanoli, 1979). It is assumed that a corresponding regression also occurred in the Caspian Sea (Fig. 2), where palaeo-channels have been found at *c.* 800 m below sea-level within its southern basin (Obedientova, 1977).

There were a further five regressions of the Black Sea in the Pleistocene, during which sea-level fell by 50–150 m, exposing the greater part of the shelf. These are associated with valley formation on the shelf and canyon development within the continental slope (Fig. 2). Although it is generally accepted that regressions occurred at the beginnings of glaciations, with transgressions at the ends of glaciations and during interglacials, there is little solid evidence to confirm this idea. On the inner Black Sea shelf, alluvial infill of probable Don Glacial age is overlain by fluvial deposits of the Kolkotov Suite with faunal remains (Gozhik, 1984). The eustatic regression of the Black Sea in the Late Pleistocene, which correlates with the peak of the Last Glacial, caused considerable scour, followed by the deposition of the Ant Suite of the Lower Dnieper (Gozhik, 1982) as well as the development of drainage systems on the shelf (Scherbakov *et al.*, 1976; Dodonov et. al., 2000; Fig. 1).

Fluvial activity of the Middle and Lower Volga was interrupted in the Late Pliocene by the maximum Akchagyl transgression of the Caspian Sea. Subsequently the Lower Volga valley periodically experienced extensive marine invasions (Figs 1, 2), resulting in limited preservation of fluvial sediments. There is a widespread idea that highstands of the Caspian have resulted from meltwater influxes. However, this does not take into account the tectonic evolution of the Caspian depression and adjoining areas. In particular, Kopp & Tveritinova (2001) have suggested that active rifting in the Western Caspian Foreland Basin was an influence on the Caspian transgressions. Within the Black Sea and Sea of Azov basins, the Uzunlar, Karangat, New Euxinian and New Black Sea transgressions (Fig. 2) led to significant flooding of lower fluvial reaches and to estuary formation.

There is evidence that regression–transgression cycles led to corresponding cycles of aggradation and erosion within a restricted part of the lower valley, depending on the scale of sea-level rise. The two-member sequence of alluvium, divided in some places by estuarine deposits (see section on 'Channel facies', above), is representative of such cycles.

Other factors

North–south aligned fluvial reaches in the study area have asymmetrical cross profiles in which most of the highest and oldest Pliocene–Lower Pleistocene terraces occur east of the present channel. The right flank of the valley is steeper and generally cut in bedrock. This observation has been attributed to the Coriolis Force (Nazarenko, 1968; Obedientova, 1977). Maximal widening of the Middle Dnieper valley as a result of such migration reached 150 km in the Middle to Late Pleistocene. A rather smaller westward shift of the Don is indicated by the mapping of Holmovoi (1974). The Dnieper shifted from the axial zone of the Dnieper–Donets Depression towards the Ukrainian Shield and displacement of the Don occurred within the Voronezh Anteclise, so tectonic control can be ruled out as a cause of this one-way river migration. The strongest influence of the Coriolis Force was probably during intervals of tectonic stability or moderate uplift. Other factors to be considered include erodability of the valley bedrock, presence of karstic rocks, total thickness of rocks subject to lateral erosion and other local factors influencing the scale and intensity of erosion (Goretskiy, 1966; Obedientova, 1977; Matoshko *et al.*, 2002).

8. CONCLUSIONS

Fluvial sequences have an important place in the continental Late Cenozoic of the East European Platform and the transition zone to the Carpathian Orogenic Belt. Each fluvial suite has a unique lithofacies, allowing it to be readily identified. Correlation is based upon mammalian and molluscan biostratigraphy, with reference to non-fluvial index beds, with the addition of magnetostratigraphy. The Dniester terrace staircase is the main fluvial stratotype for the East European Plain.

Groups of fluvial series and suites for the rivers of the East European Platform (the Dnieper, Don and Volga) record two full erosion–aggradation cycles from the Miocene to the late Middle Pleistocene and one subsequent erosion phase that is still continuing. Their total valley incision during this time has been 160–200 m. In the Carpathian piedmont (the Dniester) one full cycle in the Late Miocene–Early Pliocene has, instead, been followed by 250–270 m of incision to the present. These river valleys mainly serve as arterial channels for intracontinental sediment transport with limited local deposition, although where they coincide with rift zones there are significant local depocentres.

Due to the limited data, especially geochronology, the correlations suggested here should be considered as a first effort to confront individual fluvial histories of the major rivers studied.

ACKNOWLEDGEMENTS

The authors thank David Bridgland and Rob Westaway for valuable notes and helping to improve the manuscript. Richard Preece is thanked for checking taxonomic nomenclature. This paper is a contribution to IGCP 449 'Global Correlation of late Cenozoic fluvial deposits'.

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Manuscript received 1 July 2003; revised typescript accepted 29 March 2004