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Article in Sedimentary Geology · January 1997
DOI: 10.1016/S0037-0738(96)00028-0

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The wandering of the Volga delta: a response to rapid Caspian sea-level change

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Received 4 December 1995; accepted 25 April 1996

Abstract

Due to its very low gradient and absence of tide and surf, the Volga delta is an even more extreme example of the fluvially dominated type than the Mississippi delta. However, it differs from all other large delta systems in that it borders a closed basin, the Caspian Sea, now at -26 m below global sea-level. Caspian sea-level is much more dynamic than that of the world oceans, and rises at present about 1.5 cm/yr, a hundred time the eustatic rate. Within the Quaternary, sea-level oscillations of at least 5 orders of magnitudes have been distinguished, which seem grossly out of phase with eustatic sea-level. Between the Weichselian Early Khvalyn highstand of +50 m and the Early Holocene Mangyshlak lowstand at -80 m the apex of the Volga delta has wandered over 700 km alongstream. The present-day Volga delta is not a highstand deposit but probably represents a minor transgression in a major regressional stage. The delta does not show a coarsening-upwards sedimentary sequence, but consists of a Weichselian transgressional fining-upwards sequence topped by eolian deposits, in which the delta distributary channels have been incised. Present-day sedimentation is limited to a narrow fringe along the delta front, and to deeper waters over 200 km offshore. Sea-level changes outpaced aggradation to such an extent, that Volga sediment is spread over the whole North Caspian Plain. Sequence-stratigraphical principles are difficult to apply because sea-level cycles of five orders of magnitude are superimposed, and because there is not enough sediment loading or tectonic subsidence to create sufficient accommodation space.

Keywords: delta classification; Quaternary stratigraphy; sequence stratigraphy; Russia

1. Introduction

With its drainage basin area of 1.4 million km² and fluid discharge around 7600 m³/s the Volga river is one of the largest in the world. On a worldwide perspective, its delta is the tenth in delta plain area (20,000 km²; Coleman and Roberts, 1987). The Volga river is the largest river that does not drain into the world ocean, but into a closed basin, the Caspian Sea, now at -26.3 m below global sea-level. There is hardly any salinity contrast between the outflowing Volga water and the water of the Caspian Sea (3 promille at the outermost delta border, Kosarev and Yablonskaya, 1994), making inflow essentially homopycnal (Bates, 1953). The offshore gradient is extremely gentle. At the Mangyshlak sill, 200 km

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from the delta shore line, water depth is only 10 m (Fig. 1). There is neither tide nor significant wave action, and the delta shoreline length (800 km) to width (200 km) ratio is very high. All these properties make the Volga delta an even more extreme example of a fluvially dominated delta, in the triangular classification by Galloway (1975), than the often cited Mississippi one.

The most outstanding feature that makes the Volga delta unlike any other large deltas, is the role played by fluctuations of Caspian sea-level. These are not only independent of eustatic changes, but seem to be also grossly out of phase with them (Rychagov, 1977; Varushchenko et al., 1987; Klige and Myagkov, 1992; Ignatov et al., 1993; Kaplin and Selivanov, 1995). They reflect mainly changes in precipitation in the Volga basin, which supplies 80% of its inflow, as well as changes in evaporation at the sea surface (TED Caspia, 1992; Naydyonov, 1992; Rodionov, 1994; Malinin, 1994). Within the last 70,000 years sea-level has been as much as 75 m above (Rychagov, 1977; Svitoch, 1991) and possibly even 80 m below the present one (Maev, 1994). In a more distant geological past changes might have been even more extreme.

The onshore part of the Volga delta occupies less than 5% of the enormous North Caspian Basin (500,000 km², including the northern part of the
Caspian Sea). Because of the extremely gentle onshore and offshore gradient (5 cm/km), transgressions and regressions have a profound effect on the position of the delta itself. While the distance from apex to shore of the present delta is not more than 100 km, sea-level fluctuations have caused alongstream displacements of the delta apex over a distance of 700 km (Svitoch, 1994; Svitoch and Yanina, 1994). Furthermore, also lateral shifts in the position of the delta apex have occurred (Belevich, 1970). This delta shifting implies that the Volga River has wandered freely in the North Caspian Basin. The sedimentary architecture of the Volga delta, therefore, strongly differs from that of all other large deltas.

Understanding the dynamics of the Caspian Sea, and, for that matter, its largest wetland area the Volga delta, is the more important, as after a period of prolonged sea-level fall from 1930 to 1977, when it dropped to -29 m, it is now rising again at a rate of 15 cm a year (Fig. 2), a hundred times faster than actual eustatic sea-level rise. This rise threatens large areas with inundation, pollution, and ecological changes (TED Caspia, 1992; Kasimov et al., 1995a,b). For this reason, the Caspian Sea shores are perhaps the best modern sites to study the effect of sea-level rise on coasts (Ignatov et al., 1993; Kaplin and Selivanov, 1995).

Geomorphological and stratigraphic research in the Volga delta has a very long history in Russia (Klyonova, 1951; Leont'ev and Foteeva, 1965; Leont'ev et al., 1977; Svitoch and Yanina, 1994), but very little of this has been published in the English-language literature apart from a few sections in the textbook of Zenkovich (1967) textbook. This paper aims to integrate existing data on morphology, sedimentation, and stratigraphy into a framework that allows for comparison with other great delta systems of the world.

2. Geological setting

The Volga River drains the dissected Eastern European Platform, consisting mainly of Mesozoic sedimentary rocks, covered with moraines, loess and alluvial deposits. The North Caspian Basin (Fig. 1) in which it flows out near Volgograd is a very deep, almost circular sedimentary basin located on top of the southern border of the Eurasian plate. It has never been affected by orogeny, so that it contains a virtually undisturbed 22 km thick sedimentary record from the Precambrian to the present day (Dolginoow and Kropatschjow, 1994; V.L. Sokolov, 1970 cited in Khain and Lomize, 1995). Deformation of this sedimentary body has been due to halokinetic movements of over 1500 Zechstein salt domes, and to vertical dislocations along E–W-trending uplifts (Leont'ev and Foteeva, 1965). The North Caspian Basin is an important reservoir for hydrocarbons, such as the Tengiz oil fields in Kazakhstan and the gas condensate wells near Astrakhan.

The history of the Caspian Sea as a closed basin dates from Akchagyl (Late Pliocene) times onwards, as this water body was severed from the Paratethys Sea by orogeny in the Caucasus (Nevesskaja et al., 1984). The average thickness of the Quaternary amounts to a few tens of metres, but may locally reach a maximum of 350 m (Bogdanov, 1934;
Rachkovskaya, 1951; Leont’ev and Foteeva, 1965; Zhidovinov et al., 1981; Svitoch, 1991). These sediments record a complex pattern of transgressions and regressions, with an estimated vertical amplitude of over 100 m. Although the accumulated thicknesses by themselves record a considerable basin subsidence, the levelling record of the last century shows that the Volga delta area is subject to uplift up to 3 mm/y (Lilienberg, 1985, 1993).

3. Present-day delta dynamics

The onshore part of the Volga delta (Fig. 3) occupies about 20,000 km², with a distance from apex to coast of 105–120 km and a highly indented coastline of about 800 km shore line length at a delta width of 200 km. The Volga delta is very flat: the apex north of Astrakhan is situated at −22 m absolute elevation, the present-day (1995) shoreline at −26.3 m (4 cm/km). The Volga discharge averages 241 km³/yr (7642 m³/s) over the period 1880-1990, but large and systematic deviations from this average have occurred, leading to rapid changes in Caspian sea-level. From 1900 to 1930 discharge averaged over 250 km³ (7928 m³/s), but after 1930 it dropped to around 200 km³ (6342 m³/s), and remained far below average until 1977. From that year onwards discharge strongly increased, averaging about 290 km³ (9196 m³/s; Klige and Myagkov, 1992; TED Caspia, 1992; Kosarev and Yablonskaya, 1994; Rodionov, 1994). As a result of discharge regulation by the construction of the Volgograd reservoir, the annual peak flood has been displaced from June to end May, while the winter low is less pronounced (Moshkalenko and Rusakov, 1979). Much is also lost by irrigation. The climate in the Volga delta itself is arid, with around 150 mm annual precipitation.

The sediment of the Volga upon entering the delta is largely very fine sand (100–150 μm), silt and clay (Klyonova and Yastrebova, 1956; Belevich, 1960; Kholodov and Lisitsyna, 1989; Svitoch and Voskresenskaya, 1993). Part of the deposits from upstream accumulate in a series of reservoirs, the nearest and most recent of which is situated in Volgograd. In the period 1950–1958 the annual suspended load averaged 13.3 mln t/year, but after the construction of the Volgograd dam it dropped to 7.2 mln t/year in 1959-1970, and in 1975-1980 to only 6.0 mln t/year, partly also due to the diminishing natural discharge of the river in these periods (Rusakov, 1989).

The present-day delta dissects a large field of E–W-stretching straight elongated hills, with heights up to 20 m above the surroundings and locally over 20 km long (Fig. 3). They are called Baer Hills, after the German explorer K.E. Baer who first described them in 1859. Most authors consider them to be longitudinal dunes formed during the Late Glacial–Early Holocene Mangyshlak regression (Rachkovskaya, 1951; Leont’ev et al., 1977), though an origin by coastal processes has also been suggested (Svitoch and Yanina, 1994).

Fig. 3. Mosaic of six Kosmos MSK images of Volga delta (June 1991). Legend: 1 = eolian sands; 2 = white, Baer hills (longitudinal dunes); black, interdune areas flooded by Volga; 3 = apical part; 4 = upper delta plain with dissected Baer Hills (short E–W white streaks); 5 = lower delta plain; 6 = Makarkin island, one of the erosional highs in the avandelta that emerged during the 1930s sea-level fall; 7 = sediment plumes from dredging the Bakhtemir shipping canal. Box indicates position of Fig. 5.
(3) In the lower delta plain below -25 m no Baer Hills are present at the surface, and this zone is mainly made up of alluvial deposits laid down since the period of sea-level lowering in the 1930s (see below). This zone shows two deep indentations further inland, the Siniye Mortso and the Kaban'-kul. These are the sites of the main Volga channels during the medieval lowstand (Derbent regression), and they were occupied by deep estuaria during the highstand of the early 19th century as seen e.g. on the map by Kolodkin from 1809 to 1814, (Belevich, 1958a; Rusakov, 1990). These two embayments are now occupied by rapidly shifting low-sinuosity channels resembling those further upstream.

The delta front, now at -26.3 m, is where active delta progradation takes place. At the very coast line over 800 outlets are found, up to 6 per km, with an average depth of 1–3 m. There are a few larger outlets, but there is no single main channel. At the outlets mouth bars are formed by deposition during high floods, which obstruct further flow, leading to flow separation, bifurcation and conversion into subaqueous levees (kosy, Figs. 5 and 6; Belevich, 1956a; Rusakov et al., 1991). The levees consist predominantly of fine sand with some admixture of clay. Because of the absence of tides and surf, there is virtually no reworking of sediment by coastal processes. The levees continuously grow seaward and accrete vertically, and they gradually emerge while a characteristic succession of fresh-water vegetation establishes itself, starting with water plants, reeds, lotus fields (*Nelumbo nucifera*), and eventually willows. Older levees consist of fine sand but have a thin cover of silt and clay deposited after the development of willow vegetation on it. The overbank deposits behind the levees are predominantly silty, with rarely more than 20% of clay (Belevich, 1960).

Areas between prograding outlets lag behind and form shallow (<1.5 m) elongated bays occupied by floating fresh water vegetation, but they still may receive some sediment during high floods. Small-scale crevassing may then take place. These bays
are called kultuky locally. During rapid progradation of the coast, some kultuky become entirely isolated from the coast and the resulting lakes are called ilmeny (Belevich, 1958b). The alternation of outlets and kultuky explains the high delta shoreline length to delta width ratio.

Landwards from the delta front, smaller creeks (yeriki) may gradually become choked with sediment and plant debris so that they loose their function, thus leading to the coalescing of small islands into larger ones. Other creeks develop into major waterways (protoki) with depths up to 3–4 m, with locally deep
water holes down to 20 m (yamy, Belevich, 1956a, 1978; Rusakov et al., 1991). In this way, the number of creeks diminishes upstream and the islands grow larger and less numerous. But taken on the whole, these constructional islands occupy only a minor part of the delta surface.

The functioning of the distributary channels has been greatly influenced by the digging of shipping canals since 1874 such as Bakhtemir (7 in Fig. 3), by the construction of the Volgograd hydroelectric power station, and by a water-separation device in the apical part constructed to ensure simultaneous flooding of the eastern and western part of the delta (Belevich, 1971; Rusakov et al., 1980a,b, 1991; Rusakov and Moskalenko, 1984; Rusakov, 1989).

(4) The avandelta (prodelta) stretches up to 80 km offshore from the present coastline with a gradient less than 5 cm/km, so that at its distal edge water depth is not more than 2–4 m (Belevich, 1963, 1965; Rusakov, 1989, 1990). Because of its shallow depth, flow velocity is still considerable, and much sediment is transported seawards across it to deeper water, unhindered by waves or tides, as can be seen in the aerospace imagery (5 in Fig. 3).

The topography of the avandelta is mainly of erosional origin, veneered with a thin layer of recent sediment (Belevich, 1965, 1969). During sea-level lowering in the thirties a number of islands emerged offshore from the outlets (Makarkin, Zyudyev) which represent the highest parts of this erosional topography (Fig. 3). A special role is played by the yearly southeastern storms (nagony), which give rise to considerable wave action on the avandelta and the shelf and lead to reworking of bottom sediment. In exceptional cases, such as in 1952, storms may force water levels to 2–3 m above normal and cause flooding up to Astrakhan (TED Caspia, 1992).

(5) Further seaward, the avandelta passes gradually into the shallow North Caspian shelf, which is not deeper than 10–12 m to the Mangyslyakh sill, 200 km from the coast (Fig. 1). The shelf edge, at 100 m depth is situated at 300 km south from the coast and forms the separation between the north Caspian Sea and the middle Caspian Sea. Both the Mangyslyakh sill and the shelf edge and slope are tectonic features (Leont’ev et al., 1977).

The avandelta and the shelf are dissected by submarine gullies (Fig. 6; borzdyny) formed by subaerial erosion during former regressions, which pass into submarine canyons downslope from the shelf edge. At water depths between 40 and 140 m, seismic profiling shows fan-like bodies of sediment (Lokhin and Maev, 1990). These deposits might represent submarine fans formed from lowstand sediments transported through the submarine canyons, or old delta systems related to deep regressions of the Caspian Sea. No borings are available from these structures.

Summarizing, large areas of the actual delta have not been formed by recent sedimentation, but are relict forms or erosional in origin, with only a thin veneer of recent sediment deposited on top of them during floods. Active constructional sedimentation only takes place in narrow zones along the distributaries, along the delta front, to some extent on the avandelta, and probably downslope from the shelf edge.

4. Recent sea-level changes

The dynamics of the Volga delta are closely related to climatic changes in the Volga basin and in the Caspian Sea area itself. The recent sea-level rise seems to be due to a combination of higher Volga discharges and lower evaporation from the Caspian Sea surface, in relation with changes in the persistence of southwestern circulation patterns (Klige and Myagkov, 1992; Rodionov, 1994), but its cause is still a much debated question (TED Caspia, 1992; Naydyonov, 1992). The combination of increasing Volga discharge and sea-level rise leads to accelerated vertical growth of sediment bodies, and eventually onlapping sedimentary sequences. Lowering sea-levels lead to increased channel erosion and rapid seaward progradation of the delta at lim-
Figs 7. Delta progradation since 1826 (after Klyonova, 1951; Anonymous, 1985).

ited vertical aggradation, giving rise to offlapping sequences. The observations of Belevich (1956a,b, 1958a,b, 1960, 1965) on progradational processes in the Volga delta refer to a period of decreasing discharge and lowering sea-level before 1977, while data reported by Rusakov (1989, 1990) and Rusakov and Rybak (1995) mainly refer to the present period of sea-level rise (Fig. 2).

In historic times, at least during the last 500 years, the effects of sea-level changes were largely confined to the limits of the present-day delta, as the level of the Caspian Sea probably did not surpass −25 m (Rychagov, 1993a). There is a record of seaward delta growth from 1814 onwards (Fig. 7; Anonymous, 1985), though of low cartographic precision and with notable discrepancies between the authors that studied this issue (Rusakov, 1989). It has been monitored by yearly observation of the growth of natural levees at the mouths of the major distribu-
tory channels in the three parts of the Astrakhan nature reserve. From 1814 to 1925, at roughly con-
stant or slightly lowering sea-level around −25 m (Rychagov, 1993a), delta growth rate appears to have been rather constant, around 250 m/y shoreline advance, as measured by repeated leveling and bathymetry using vertical iron rods as reference points (Goremykin, 1970; Rusakov, 1989). Seawards growth accelerated during the 1930s up to over 400 m/y, when an abrupt sea-level drop of about 2 m occurred within seven years (Fig. 2). Growth rates
remained high between 100 and 250 m/year until, as a result of the construction of the Volgograd dam in 1959, delta progradation slowed down considerably to rates around 40 m/year (Belevich, 1960, 1963, 1978; Goremykin, 1970; Rusakov, 1989). However, there is considerable uncertainty as to the reliability and the comparability of the data, and the development in different parts of the delta is probably neither synchronous nor of equal rate.

Comparison of satellite imagery of the delta since 1977 shows that the coastline is virtually unchanged up to the present day (TED Caspia, 1992). This apparent stability means that due to sea-level rise delta progradation has virtually come to a standstill, and most of the sediment delivered by the Volga is accumulating on top of previously existing bars. The images show only insignificant retreat of the coastline because vegetation (especially reed and willows) continues to mark the location of levees long after they have been submerged by sea-level rise. Vegetation changes in formerly dry parts contained within levees are considerable. In the avandelta the greater water depth is leading to increased wave action and disappearance of sea grass beds (Rusakov and Rybak, 1995).

Vertical accumulation rates in the avandelta (prodelta) are estimated between 3 and 13 mm/year according to different authors (Klyonova, 1951; Belevich, 1956a; Rusakov, 1989), but the observations are so fragmentary that it is difficult to detect a trend in them. The deposits of both the modern levees and those from the 1930’s do not surpass 2 to 2.5 m in thickness. This would suggest that little vertical aggradation has taken place since the 1930’s. Indeed, according to Belevich (1956a) the natural levees grow upward rapidly in the first five years of their formation, after which stabilization takes place. Inasmuch as seaward progradation is no longer taking place and water depths in the avandelta are increasing, vertical accumulation might be expected to increase, but no reliable information is available.

5. Quaternary sea-level changes

Rapid sea-level fluctuations have taken place in the Caspian Sea since it became a closed basin. Svitoch (1991) subdivided the sea-level cycles in five classes based on the order-of-magnitude of their duration, four of which are shown in Fig. 8. The fifth one refers to still smaller cycles in the order of magnitude of tens of years (e.g. Rychagov, 1993a). Their main phases are well known from both onshore and offshore borings, and from the occurrence of uplifted marine terraces around the Caspian Sea.

From the time of its formation as a closed basin in the Pliocene, at least six major transgressional phases have been distinguished, named Akchagyl and Apsheron in the Pliocene, and Baku, Khazar, Khvalyn and Novocaspian in the Quaternary (Fig. 8; at least part of Apsheron would be Pleistocene according to modern nomenclature). Whereas their relative age and correlations are well known through the occurrence of characteristic mollusc assemblages (Svitoch, 1991), there is considerable uncertainty as to their absolute age. Apsheron sediments from Azerbaijan show reversed magnetization (Trubikhin, 1987) and intercalated volcanic ashes give a fission track age of 0.96 Ma (S.S. Ganzey, cited by Mamedov and Alekserov, 1991). Apsheron terraces in Dagestan (western Caspian shore, just south of Fig. 1) occur around 300 m absolute height. All four subsequent phases appear to be normally magnetized, and thus are of Brunhes (<70 ky) age (Rychagov, 1977; Trubikhin, 1987). From the two main Baku marine terraces in Dagestan with absolute heights of 200-220 m TL ages between 400 ± 48 ka and 480 ± 53 ka have been obtained (Rychagov, 1977), while volcanic ashes enclosed in Baku sediments from Azerbaijan have been fission-track dated at 510 ka (Koshkin, 1984, cited by Mamedov and Alekserov, 1991). The main Khazar terraces between 170 and 80 m in the same area give ages between 100 and 125 ka (Shakhovets and Shlyukov, 1987). While there is little disagreement as to the age of these deposits, the absolute height reached by these transgressions and the intervening regressions is still hotly debated (Varushchenko et al., 1987; see also below).

In the Khvalyn terraces in Dagestan two major phases have been distinguished. The Early Khvalyn transgression is represented by five successive marine terraces between +50 and 0 m absolute height, and the Late Khvalyn transgression by at least four successive marine terraces between 0 and
Fig. 8. Plio-Quaternary transgressions of the Caspian Sea. Major regressions are indicated with double lines. Third and fourth column give absolute heights of Khvalyn and Novocaspian coast lines (compiled after Rychagov, 1977; Leont’ev and Foteeva, 1965; Svitoch and Yanina, 1994).

-20 m absolute height (Rychagov, 1977). The deep Yenotaev regression between the Early and Late Khvalyn transgressions may have reached down to 80 m below present sea-level (Maev et al., 1989; Maev, 1994). The +50 m Early Khvalyn terrace level is also referred to as called ‘maximal transgression’. Deposits of the maximal transgression form the highest level at the surface in the whole North Caspian Basin, and there is evidence of the existence of an overflow to the Black sea at +50 m through the Kuma–Manysh depression north of the Caucasus (Menabde and Svitoch, 1990).

There is still total disagreement on the age of the Khvalyn transgression, though all ages are within the range of the Weichselian (Valdaian) glacial stage (isotopic stage 4-2). Early Khvalyn sediments from outcrops in the North Caspian Plain between Volgograd and the 0 m contour (Figs. 1 and 11) give TL ages between 24 and 26 ka, which are rather close to a 14C age of 34 ka on organic matter from one of the profiles (Shakhovets and Shlyukov, 1987). The Khvalyn marine terraces in Dagestan consistently range in age between 70 ka for the uppermost (oldest) ones to 14.6 ka for the lower (youngest) terrace according to TL dat-
ings (Rychagov, 1977). However, these same terraces all gave \(^{14}C\) mollusc ages between 15 and 8 ka, and are indistinguishable by this method. Also U–Th ages are in the range of the \(^{14}C\) ages (Rychagov, 1977). While Rychagov (1977) accepts the TL ages as being the most reliable on the base of their geomorphological consistency, Svitoch (1991) argues for acceptance of the \(^{14}C\) ages on the basis of their proximity in age, their coincidence with the U–Th datings, the fact that they have been obtained by different laboratories and are in the optimal range for this type of datings. In his view, part of the Khvalyn is Early Holocene (see also Svitoch et al., 1987, 1993; Kaplin et al., 1993). However, \(^{14}C\) datings of molluscs might be unreliable because of age resetting by the aragonite–calcite transition (Bradley, 1985).

There is as yet no final answer to this question. The age of the maximal transgression, 70 ka, 25 ka or 15 ka, is of primary importance to solve the problem of synchronicity of Caspian sea-level changes with global climate change.

The most detailed knowledge on Holocene sea-level comes from the Turalli–Sulfat section along the Dagestan coast described by Rychagov (1977,b). Up to 5 transgressional phases have been described and \(^{14}C\) dated (Figs. 8 and 9) around 8000 BP, 7000 BP, 6000 BP, 3000 BP and 200 BP. The maximal absolute height of the Caspian Sea reached during these transgressions is around \(-22\) m, which means that the Holocene sea-level did not surpass the level of the apex of the present-day delta. The depth of the intervening regressions is much less clear, however. According to Maev et al. (1989) the Mangyshlak regression at the start of the Holocene might have reached the \(-50\) to \(-70\) m isobath, and the Derbent regression around 1500 BP at least attained the \(-34\) m isobath, leaving a major part of the present-day shelf down to the Mangyshlak sill exposed.

6. Quaternary stratigraphy of the Volga delta

Sediments of the six major Plio-Quaternary transgressions have been found in many borings in the Volga delta (Fig. 8; Bogdanov, 1934; Rachkovskaya, 1951; Zhitovinov et al., 1981; Svitoch, 1991; Svitoch and Yanina, 1994). They overlie Cretaceous and Palaeogene Tethys sediments with an erosional unconformity. The total thickness of the Quaternary sediments (Baku and younger) amounts to several tens of metres, with a maximum of 364 m reached at one spot in the western part of the delta. Baku sediments are found as a rule below 90–75 m depth, and consist of grey clays with intercalations of brown sands, with an average thickness of 30–40 m. Khazar sediments are encountered at 10–12 m depth. They consist mainly of clays with sandy intercalations, and their thickness does not exceed 30–40 m. Both Baku and Chazar sediments show alternations of fresh-water and saline mollusc assemblages, recording several smaller transgressions and regressions.

A more complete picture is available of the distribution of the Khvalyn and Novocaspian sediments in the area of the present-day Volga delta. Rachkovskaya (1951) shows a number of cross-sections based upon a series of 51 borings up to 20 m depth in which a complete sequence of Khvalyn
sediments is present (Fig. 10). The sequence rests on Upper Khazar sediments with an erosional unconformity corresponding with the Atel’ regression (Fig. 8). Elsewhere in the North Caspian Basin this unconformity takes the form of erosional valleys up to 25 m deep and filled with sand (Svitoch and Yanina, 1994). The Khvalyn sequence is essentially a fining-upwards sequence, starting at the base with sands, followed by silts, and topped by characteristic brown clays called ‘chocolate clays’ locally. These clays correspond with the +50 m Early Khvalyn maximum transgression, and are found at the surface throughout the Northern Caspian Plain, with a slight seaward dip because of basin subsidence. The ubiquity of the chocolate clays shows that the Khvalyn sequence in the North Caspian Basin is essentially transgressional, reflecting a gradual deepening of the basin. In the Volga delta area the chocolate clays are overlain by the mostly eolian Baer hills sediments probably related to the deep Early Holocene Mangyshlak regression (cf. Figs. 8 and 10b, c).

Novocaspian (Holocene) sediments are mainly found in erosional valleys up to 20 m deep, now occupied by Volga distributaries. These valleys probably were scoured out during the Early Holocene Mangyshlak regression following the Late Khvalyn highstand. They have sand fills at the base, passing upwards into silty deposits, reflecting drowning during later Holocene transgressions. During the subsequent sea-level drop sandy and silty fluvial sedimentation took over. In smaller distributaries only fluvial sediments are found.

Only in the lower delta plain, a narrow strip of about 20 km along the delta front, a more or less continuous wedge of Holocene sediments is present, with an average thickness around 10 m, thickening to 20 m at the site of the major scours, and tapering out again seawards to a thickness of 2–3 m (Fig. 10b, c). The succession consists of rapid alternations of bar and levee sands, laminated overbank silt and clay, and organic rich kultuk and ilmen (marsh) deposits, with a great lateral variability, corresponding to the intricate sedimentation patterns at the present delta front. Preliminary 14C datings on organic matter from these sediments give ages of 1010 ± 40 BP (GrN-21063), 2930 ± 50 BP (GrN-21064) and 4150 ± 80 BP (GrN-21065). The subsurface data indicate that the Volga delta, in contrast to other large delta bodies in the world, only consists partially of its own recent sediments.

7. Location of Pleistocene Volga deltas in the North Caspian Plain

The first traces of a Pliocene (pre-Akchagyl) Proto-Volga valley have been found in the foothills of the Obshche Syurt north of the Caspian Basin, far to the east of the present course (Fig. 1; Svitoch and Yanina, 1994). Relatively little is known on the position of the Volga delta during Akchagyl (Pliocene), Apsheron, Baku and Khazar times, because all these deposits are buried beneath younger sediments. Alternation of saline and fresh-water mollusc assemblages in these deposits testify to the fluctuation of sea-level and the varying influence of fluvial processes.

Traces of the Khvalyn deltas during and after the maximal transgression of +50 m, however, are found at the surface throughout the Northern Caspian Basin (Fig. 11; Nikolaev, 1957; Leont’ev and Foteeva, 1965; Belevich, 1970; Leont’ev et al., 1977; Svitoch and Yanina, 1994). At the maximal transgression, the North Caspian Basin was flooded in its entirety, and the Volga flowed into the Caspian Sea through a narrow estuary in the present-day course far north of Volgograd (Fig. 11). It is in this stage that deposition of the chocolate clays occurred. The successive stages of Volga deltas that formed after the maximal transgression are shown in Fig. 11. The delta formed between the Volga and the now defunct Sarpa branches is particularly well developed topographically: it consists largely of wide erosional valleys which bifurcate and unite again, and which end blindly at absolute altitudes between +12 and +7 m. This feature might be coeval with one of the Early Khvalyn marine terraces at similar height along the Dagestan coast (Rychagov, 1977). A similar complex is found further south at absolute heights between +2 and 0 m. There is surprisingly little sediment in these valleys, and they are referred to by Leont’ev and Foteeva (1965) as dissected deltas.

An even more clear illustration of the periodicity in the formation and subsequent dissection of deltas during smaller sea-level oscillations after the Khvalyn highstand is shown by the Ural river, the neighbour of the Volga in the North Caspian Plain.
Fig. 10. Cross-sections Volga delta: (a) location of sections; (b) transversal sections (1, 2, 3); (c) longitudinal section (4); nk = Novocaspian; hv = Khvalyn; hz = Khazar. Hummocks at the surface represent cross-sections of longitudinal dunes (Baer Hills) (simplified after Rachkovskaya, 1951).

(Fig. 11, Leont’ev and Foteeva, 1965; Leont’ev et al., 1977). This river shows a string of at least seven delta systems along the axis of the present course, each of them with distributaries incised into the Khvalyn chocolate clays. The Late Khvalyn deltas below the 0 m contour are less well visible because of a persistent cover with eolian sands, including the Baer Hills (Fig. 3).

After the formation of the Khvalyn dissected deltas the deep Mangyshlak regression took place, leading undoubtedly to the formation of delta systems possibly as deep as 80 m below the present-day sea-level (Maev et al., 1989; Maev, 1994), as well as to the formation of submarine fans (Lokhin and Maev, 1990).

The present day Volga delta is dissected as well, as its distributaries incised during the regression that followed the Khvalyn highstand. The Novocaspian transgression filled the deepest scours, but did not rise high enough to completely drown the upper delta plain.

8. Discussion: sedimentary architecture of the Volga delta

In the last twenty years, the architecture of sedimentary basins has been studied in the conceptual framework of sequence stratigraphy, triggered by the wealth of data obtained from seismic surveys (Van Wagoner et al., 1988). Sea-level, tectonic subsidence and sediment supply are the main controlling factor in building a sediment body. The basic sedimentary unit is a sequence, which represents one full eustatic cycle from highstand to lowstand and up to the next highstand. An ideal sequence can be subdivided into four systems tracts, each representing a particular stage in the sea-level curve: highstand systems tract, lowstand systems tract, and the transitional stages between them. The systems track in turn consists of parasequences, the fundamental building stone of a sedimentary sequence.

Now while in the original concept a eustatic cycle, and hence the time needed to build a sequence, was taken in the order of magnitude of 1–2 Ma (third-order cycles of Haq et al., 1988), it soon became
apparent that the pace of sea-level changes has been quite different in the last 2 Ma due to glacioeustasy (Mitchum and Van Wagoner, 1991). A complete Quaternary sequence corresponding to a full sea-level cycle of over 100 m amplitude can be formed during a single orbitally forced Milankovich cycle of only 0.1 Ma duration. Time scale and spatial scale are therefore not necessarily related in sequence stratigraphy.

Caspian sea-level is much more unstable than eustatic sea-level, and strict application of the sequence-stratigraphy nomenclature to Caspian Sea sediments requires assessment of what scale of sequence is to be taken as representing the main cyclicity. From the discussion it is clear that sequences corresponding with at least five orders of magnitude of Caspian sea-level change are superimposed. Whereas in other sedimentary basins the basic sedimentary unit, the parasequence, corresponds to systematic changes in sedimentary environment at a particular rate of sea-level rise or fall, in the Caspian, on the contrary, each small-scale sedimentary unit might represent a full small-scale sea-level cycle in its own right. The sequence corresponding to the sea-level cycle between 1930 AD and 1996 AD with an amplitude of only 3 m (Fig. 2) is just as legitimate a sequence as the Khvalyn sequence (Fig. 10) deposited between +50 m Early Khvalyn highstand and the -80 m Mangyshlak lowstand. So far there is not enough factual information available on the Quaternary architecture of the North Caspian Basin to resolve all those nested sequences. We will therefore refrain from a strict application of sequence-stratigraphic nomenclature.

All modern large deltas bordering the oceans are highstand systems tracts consisting essentially of their own sediments (e.g. Wright and Coleman, 1973). They are in a constructional phase, and have pro-
graded seaward in the Holocene during a time of prolonged sea-level maximum. This results in a characteristic coarsening-upwards succession of sedimentary facies, as documented from numerous modern and ancient deltas (e.g. Elliott, 1986, 1989; Postma, 1990, 1995). Holocene deltaic sediments usually overlie Pleistocene fluvial or eolian sands deposited during the Weichselian lowstand and earlier Holocene transgressional phases. During each Pleistocene interglacial highstand sedimentation reestablished itself at more or less the same site, leading to the formation of a sedimentary wedge of considerable thickness and extent. Minor sea-level fluctuations within the Holocene highstand are probably unimportant.

The present-day Volga delta, however, is not a highstand delta. It is situated somewhere between the +50 m Early Khvalyn highstand and the -80 m Mangyshlak lowstand. The North Caspian Plain shows what a delta plain looks like long after a highstand has passed (Fig. 11). Whether the actual delta is in a regressive stage or in a transgressional one is again a matter of time scale. Seen in the perspective of the Khvalyn highstand, it is probably regressive, but in the light of sea-level fluctuations in the last century, it is transgressional since the 1977 lowstand.

The Volga delta at its present site does not show a coarsening upwards architecture either. The cross-
sections of Fig. 10 show a fining upwards sequence representing the Khvalyn transgression, but there is no phase of delta building visible except for a narrow sediment wedge in the lower delta plain. The last highstand apparently was too short-lived to build a substantial progradational deltaic sediment body, and on most sites the chocolate clays of the transgressional systems tract mark the top of the highstand. The ensuing Mangyshlak regression led to dissection of the highstand deposits by the incising distributary channels, and eolian sands started to form. The Novocaspian transgression succeeded in filling part of the deeper channels of the dissected Volga delta, and led to limited vertical accretion of sedimentary wedges along the delta front, but did not reach high enough to cover the traces of the dissected delta altogether.

The reason why the Volga delta deviates so much from other major deltas is in the combination of low gradient and rapid sea-level changes. In the present-day Volga delta, the onshore and offshore slope are equally gentle, 5 cm/km, gentler than any other major delta system (Fig. 12). The offshore part of the delta is in fact a partly drowned continuation of the North Caspian Basin and there is no clear slope break until 200 km offshore. The gradient is so gentle and the North Caspian Plain is so vast, that small sea-level changes cause large horizontal displacements of the Volga delta. Its apex has wandered over a horizontal range of 700 km alongstream (Svitoch, 1994; Svitoch and Yanina, 1994) and over a vertical range of at least 84 m, between the maximal transgression coast line at +50 m and the Mangyshlak sill at −34 m (Fig. 11), whereas the vertical range of the present-day delta is only 4 m from apex to delta front. The present-day extension of the onshore Volga delta represents less than 5% of the total basin surface. Moreover, the Volga river has not always entered the North Caspian Basin from the present-day entrance near Kamyshin and Volgograd, but has shifted laterally within the North Caspian Basin, as is shown by the reconstruction of Khvalyn deltas (Fig. 11). All this makes that Volga sediment is spread thinly over the whole expanse of the North Caspian Basin, separated by numerous closely spaced low-angle (Type II) unconformities. It takes a period of prolonged constant sea-level, a steeper gradient, and an apex fixed throughout time to build a larger delta body.

The independence of the sea-level regime and the gentle gradient of the basin are ultimately controlled by tectonics. The North Caspian Basin is situated essentially on continental crust, and shows little evidence of rapid subsidence under the weight of a delta body or by other tectonic processes. Spreading out Volga sediment over the whole North Caspian Basin reduces the load stress on the underlying crust, whereas in other deltas focused sedimentation is an important factor in subsidence and in creating accommodation space for continued aggradation at one site.

Many questions remain unsolved or await further study. In the first place the unique situation of the Volga delta being in a regressive stage enables study of sequence stratigraphical problems elsewhere.
only visible offshore. The sea-level rise of the last 15 years moreover offers a physical model for future eustatic sea-level rise elsewhere.

An awkward question unsolved up to now is the precise age of the Khvalyn highstand and following regressions. Answering this question is of utmost importance to confirm or refute the synchronicity of Caspian sea-level changes with global climate changes. An Early Weichselian age of 70 ka BP for the Early Khvalyn highstand would imply that the Caspian was at its maximum when the oceans were low, possibly indicating asynchronous temperature and precipitation changes over the East European platform. A Mid-Weichselian age around 25–30 ka would coincide with the Mid-Pleniglacial moist period, a Late Glacial–Early Holocene age for this highstand could be explained by deglaciation of the Scandinavian ice cap.

At last it is tempting to look for equivalents for the Volga delta in the fossil record. Deltas morphologically similar to that of the Volga river might be the old shoal-water lobes of the Mississippi (Frazier, 1967; Elliott, 1986), and possibly some fluvially dominated deltas in cratonic basins in the Carboniferous of northern Europe (Elliott, 1986, 1989), but neither of these is likely to have such a small gradient and to be so influenced by sea-level fluctuations as the Volga delta. The search for fossil equivalents of the Volga delta and the North Caspian Basin may contribute to a better understanding of hydrocarbon and coal occurrences elsewhere.

9. Conclusions

The Volga delta differs in many aspects from other large delta systems in the world.

1. It is forming in a closed basin with its own, highly unstable sea-level regime unrelated to eustatic changes.

2. Its gradient is more gentle than in any other major delta.

3. The present-day Volga delta does not show a coarsening-upwards sedimentary sequence. Its distributaries are incised into an older transgressive fining-upwards sequence capped by eolian deposits. In fact the Volga delta is a dissected delta. Only in the lower delta plain there is a fringe of recent sediments.

4. It does not represent a major highstand, but probably a minor transgression in a phase of prevailing sea-level fall.

5. Small sea-level oscillations are translated into large displacements of the Volga delta. Sea-level change generally outpaces accumulation. The Volga delta has wandered freely in the basin with such a speed that it has not been able to build up a substantial body of deltaic sediments.

6. Simple sequence-stratigraphical principles are difficult to apply, as the sedimentary architecture of the Volga delta and the North Caspian Plain has been affected by Quaternary sea-level oscillations of five orders of magnitudes.

Acknowledgements

This paper was written during a short sabbatical stay of the first author at the Faculty of Geography of Moscow State University. Prof. Dr. N.S. Kasimov, Dean of the Faculty is thanked for his hospitality and for his permission to use the facilities of the faculty. Dr. G.A. Krivonosov, director of the Astrakhan Man and Biosphere Reserve is thanked for his cooperation and field assistance. The Agricultural University Wageningen funded the stay in Moscow of the first author. Dr. A. Veldkamp, Ir. K. Groenesteijn, Ir. I. Overeem, Dr. A.D. Miall, Dr. H.H. Roberts and an anonymous referee are thanked for their valuable comments. The drawings were made by Mr. Piet Kostense. Part of the research for this paper was funded by NWO (grant 07-30-180) and INTAS (grant 94-3382).

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