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Studies of Recent Changes in the Caspian Coastal Zone of Russia Based on Aerial and Space Imagery

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ABSTRACT

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Comparison of aerospace pictures of the Caspian coasts of Russia taken during periods of regression (1977–1978) and transgression (1982–1992) has shown that influence of sea level rise is increases from the north to the south along with increase of offshore gradients and transition from predominantly depositional type of the coast to prevailing erosion one. At the northern part of the area (with exception of the section near the Volga delta with its "buffer" effect) flooding of mud flats and some landward retreat of all coastal complex are the typical features of coastal zone dynamics. At the southern part of the Caspian coasts of Russia transgressive transformation displays within more narrow strip. Active wave reconstruction with cliff erosion at steep slopes and large beach ridge formation with wide lagoon behind it—at more gentle slopes—are the most important feature here.

ADDITIONAL INDEX WORDS: *Sea level rise, mud flats, lagoon formation, cliff erosion, satellite images interpretation.*

INTRODUCTION

The recent rise of the Caspian Sea level since 1978 amounted to about 2 meters and induced essential changes within the coastal zone. It would be important to follow the character of the resulting changes along the coast because some forecasts predict a sharp acceleration of the World Ocean level rise in the nearest future. A response of the coastal zone to this phenomenon is as if modelled in the Caspian Sea in the course of its recent rapid transgression. Study of present-day changes in the Caspian coastal zone has also a practical aspect and could be useful in choosing the best strategy in the economic activities within coastal areas under conditions of transition from regressive to transgressive regime of the sea level.

METHODS AND MATERIALS

Changes in the Caspian coastal zones that occurred during the recent transgression have been thoroughly studied by means of comparative interpretation of aerial and space photographs taken at different times. The following materials have been used in the comparative analysis: the regression period—high altitude aerial photos at scales 1:100,000 to 1:200,000 taken in 1977–1978 and space imagery obtained from the "Salyut" space station, 1975; the beginning of the transgression (primarily 1982 to 1986) has been studied using spectrozonal space photographs taken from the "Cosmos" satellites at scale 1:200,000, resolution 10–12 m, and multispectral photos taken from the "Salyut-6" space station, original scale 1:200,000, resolution 20 m; the present-day characteristics have been obtained from spectrozonal and multispectral "Cosmos" satellite imagery taken in 1991 and 1992 at scales 1:200,000 and 1:600,000 with resolution of 10 and 15 m, respectively. For interpretation, colour prints have been done from spectrozonal negatives (1:600,000) which show best the coastal features, and vegetation in particular. Zonal prints, 1:200,000, in the red and near infrared bands were also used, which appeared to be most reliable source of information on various water bodies and the coastline position. Besides, scanner images obtained from the "Resourse-01" satellite, 1992, with 40 m resolution and 1:200,000 scale were used.

With a few exceptions, a majority of the photos studied were taken at the same season (in June–July); it is essential for reliability of the imagery interpretation, as the Caspian coast of Russia (its northern part, in particular) is subjected to considerable seasonal fluctuations of the sea level resulting from the Volga spring floods.

RESULTS

The comparative interpretation of the enumerated photo materials resulted in a series of schemes showing changes in the coastal zone due to the marine transgression within 8 sectors of the Russian coast (Figure 1); those are: (1) Kalmykian coastal zone, northern part, (2) Kalmykian coastal zone, southern part, (3) coast near the Bryanskaya and Suyutkina spits, (4) the former delta of Terek, (5) the Agrakhan Peninsula, (6) the Sulak delta, (7) the Daghestan coast near

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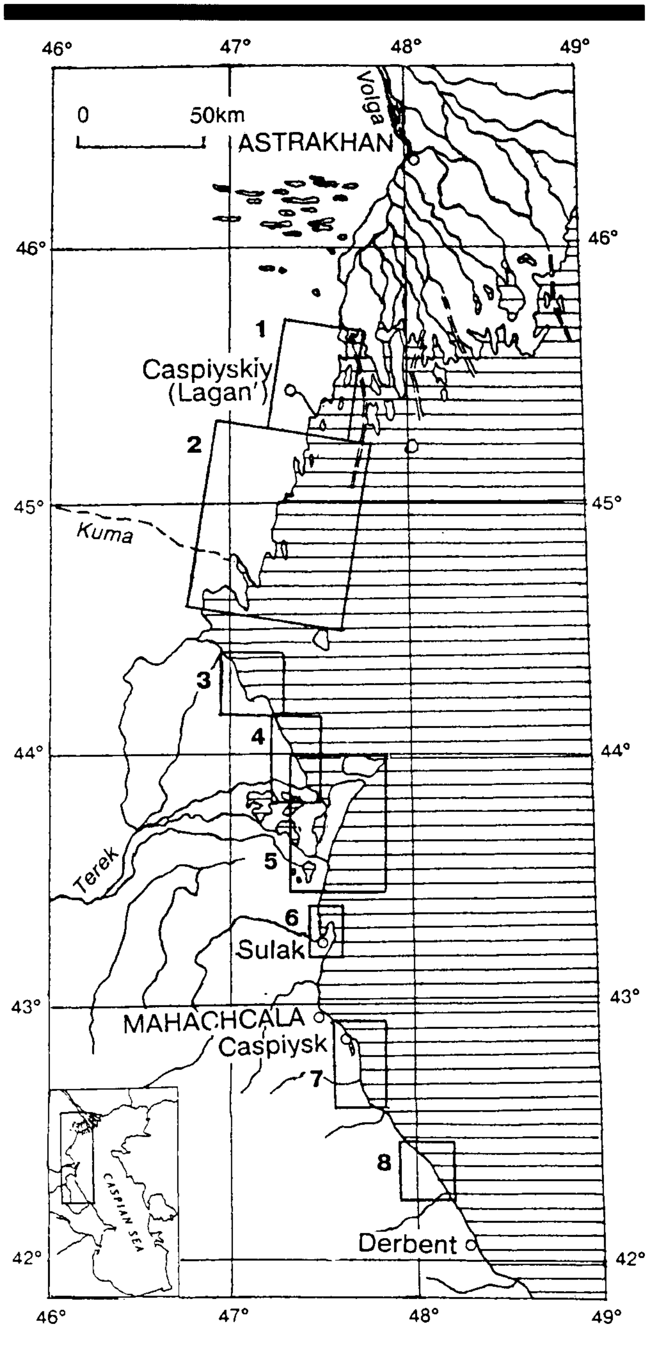

Figure 1. Location of sectors of the Caspian coast of Russia used as key sites in the interpretation of aerial and space photos taken at different time.

the city of Caspiysk, (8) Daghestan coast near the Adji Lake. All the sectors chosen feature most conspicuous changes in the coastal zone morphology.

The Kalmykian Coast, Northern Part

The whole coastal zone of Kalmykia is distinguished for prevalence of gently sloping coasts fringed by mud flats (Leontyev and Khalilov, 1965; Leontyev *et al.,* 1977). A wide longshore zone is densely overgrown with reed which makes difficult the identification of the water edge; the latter varies over a wide range due to wind-driven surges. The photos, however, show quite distinctly the outer limit of the reed growth on the mud flat. Though individual plants may grow at a depth as great as 2 meters, the reed growth on the Kalmykian coast have never been reported beyond the depth of 0.5 to 0.7 m; it may be accounted for by some local factors (probably, an effect of fringing currents due to river water inflow) which increase their negative impact on plants with depth. Formerly, 1-meter isobath followed the outer limit of the reed growth at a distance of some 5 to 6 km. It is not inconceivable that any changes in the depth suitable for the plant growth resulting from passive rise of the sea level, wave erosion or deposition on the sea floor would lead to a shift of the reed growth edge landward (in case of depth increase) or seaward (in case of deposition and the coast accretion). Therefore, any shifts in the seaward edge of the reed vegetation may be used as an indirect evidence of certain dynamic transformations within the coastal zone. This assumption was widely used in the interpretation of the aerial and space imagery.

The interpretation showed (Figure 2) that the recent sea transgression (1978–1992) caused but little changes in the position of the reed-covered flat outer edge in the northern part of the Kalmykian coast (between the Vyshkinskaya Spit peninsula and the Lagan' region). This may be attributed to the influence of the adjoining vast shoal of the Volga prodelta which acts as a buffer of a sort and attenuates the effect of the rising sea level. According to current views (Mikhailov *et al.,* 1993), this effect would last until the sea level reaches −26.5 m; after that, it would be the sea level rise and not the river inflow that controls principal processes and phenomena on the low coasts adjoining the prodelta.

The mentioned above accounts for the fact that while the sediment deposition was most typical process of the preceding prolonged period of the sea regression, it still continued along the north Kalmykian coast bordering on the Volga prodelta during the transgression. The deposition is most pronounced in the heads of bays located between the shore cusps typical of this part of the coast (north of the Vshivy Peninsula, along the Ilmen-Tatarskaya trough); individual locations 2 to 3 m wide show the coast accretion by 0.5 to 1 km.

In the south of this coastal sector the sea level rise effect is somewhat greater; the reed-covered flat doubled its width (from 1 to 2 km) advancing landward. A lagoon of intricate shape and 1–2 m wide appeared at the back of the reed flat; it is fed by wind-induced surges and groundwater, the latter rising with the rise of the sea level. The landward edge of the lagoon is fringed with waterlogged strip. A certain increase in moisture is recorded within the coastal area: some waterlogged patches appeared along the Caspiysk Canal, as well as several lakes and reed marches in depressions.

Rather conspicuous "internal" changes are seen in space imagery in the Caspiysk (Lagan) region. Vast areas of meadows, pastures and fields appeared flooded with wind-driven water detained by a system of dams. The latters were built previously for the purpose of increasing soil humidity by way of detention of the sea water which is essentially freshened

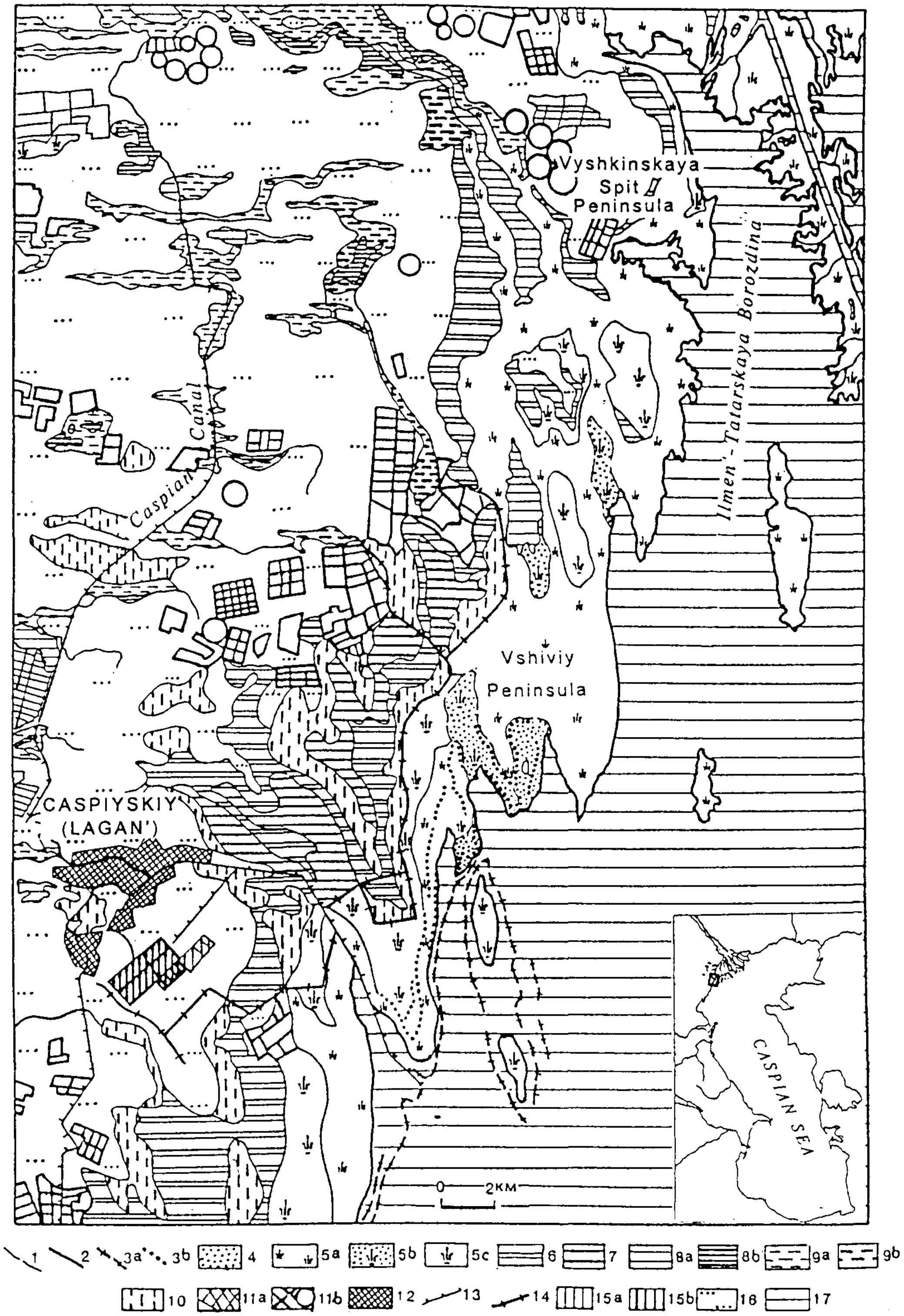

Figure 2. Kalmykian coastal zone, northern part. (1) outer limit of the reed-covered flat and the coastline in 1978; (2) the same, in 1991; (3) marine depositional landforms (beach ridges, barriers, *etc.*) developed: (a) on open shallows, (b) on the reed covered mud flats; (4) sand flat, newly appeared (zone of the coast accretion); (5) reed-covered flat: (a) persisting, (b) newly formed in bays' heads (zone of the coast accretion), (c) developed in place of former land (zone of landward shift of the reed covered flat); (6) lagoons at the back of reed-covered flats; (7) land areas flooded by surge water retented by the dam; (8) inner water bodies: (a) persisting, (b) newly appeared; (9) reed swamps on the land: (a) persisting, (b) newly appeared; (10) waterlogged area; (11) agricultural fields: (a) persisting, (b) newly cultivated; (12) urban area; (13) canals; (14) dams; (15) sewage treatment sites: (a) persisting, (b) newly constructed; (16) land; (17) sea.

here by the Volga inflow. At present, under conditions of the transgression, the marine water accumulated behind the dams approached the town and surrounded the sewage treatment sites. As a consequence, a danger aroses that the sewage may pollute the main canal used for the town supply with domestic (including drinking) water. A part of the urban territory lies below −25 m; it has already become waterlogged in lower places, and may be flooded by marine water later on.

The Kalmykian Coast, Southern Part

This stretch of the Kalmykian coast (between the Morskoy Ivan-Karaul Island and the Kizlyar Bay) south of the Volga prodelta is marked by a certain increase in the shore slope and more pronounced effect of the sea level rise (Figure 3). The effect is seen, first of all, in a retreat of the seaward limit of the reed-covered mud flat over the whole stretch of the shoreline. The coast locally receded as much as 1–1.5 km. Some of depositional landforms in the nearshore zone—barriers and ridges—have been eroded. Sedimentation has been recorded only near the mouth of the Darginsky Bank Bay, where input of the Kuma River sediment load compensates for the sea level rise, at least in part.

At the same time, a new fringe of reed growth reappeared locally along the receding coast; it is distinguished in the photos by longitudinal stripes. The fact suggests that a series of young beach ridges is forming there; the material is supplied from eroding seaward edge of the mud flat and the upper offshore zone. The data obtained seem to disagree with formerly accepted ideas that the sea transgression onto the low Kalmykian coasts proceeds passively, without shore profile reformation and sediments redistribution by waves. The slopes in the coastal zone here (and at the water edge, in particular) appear to be steep enough for wave action manifestations.

The reed-covered flat of this region expanded noticeably landward: in 1978, it was 1–2 km wide, while at present it is as large as 5–10 km. It seems to encroach upon the land. At the back of the mud flat along the whole stretch under consideration a permanent lagoon appeared by 1991 (that is when the photo was taken), its width varying in the course of the year. The lagoon is clearly seen even in small-scale scanner images of medium resolution taken from the "Resurs-01" satellites. The colour images show a waterlogged zone about 3 km wide at the back of the lagoon; it is well distinguished by a lush vegetation against the background of the surrounding semideserts.

Region of the Bryanskaya and Suyutkina Spits

South of the Kizlyar Bay, the New Caspian (Holocene) marine plain comes directly to the sea coast. In the Holocene, as well as at present, it has been exposed to marine erosion and deposition which resulted in a series of coastal constructional landforms (which mark the position of the Holocene stadial shorelines), interspersed with cliffs which served as sources of sediments.

The Bryanskaya and Suyutkina spits (Figure 4) are the largest marine constructional landforms of the region, and correspond to the latest stages of the New Caspian basin. They were built one after another (the Bryanskaya Spit—in 16th–17th centuries, the Suyutkina Spit—in 18th–19th centuries) during high stands of the sea level. During those intervals protruding lobes of the Terek delta were actively eroded, and the prevalent southeasterlies transported resulting sediments northward and fed the growing spits.

This stretch of the coast continued to change during the last decades of the regressive stage; it was locally eroded under conditions of the increasing deficit of sediments in the coastal zone resulting from the southward migration of the Terek mouth and later—from artificial diversion of the river across the Agrakhan Spit to the sea. Wave erosion of the proximal parts of the Bryanskaya and Suyutkina spits was recorded as early as 1950s (Leontyev *et al.*, 1982), largely during wind-induced surges. A quarter of century later the sea level drop resulted in formation of a rather wide (up to 400 m) grass-covered sandy flat developed around the Bryanskaya Spit, where the offshore slope was gentle; the cliff became inactive. The Suyutkina Spit, however, continued to erode at its proximal part. During that time the coastline receded there as far as 150 to 200 m. The sediments thus produced were transported to the distal part of the spit, where the coast prograded by about the same value. Sedimentation has been also recorded at the mouths of artificial canals built for disposal of irrigation water (Bryansky and Kizlyar-Caspiysky canals). At the Bryansky canal mouth a small delta formed by 1980; it protruded about 700 m into the sea and was covered with thick reed vegetation.

The recent rise of the sea level resulted in general waterlogging of low coasts and partial flooding of the flats and clayey erosional benches at the base of some cliffs. This led, in turn, to an increase of the rate of coastal erosion and to reactivation of some formerly inactive cliffs. As before, wind-induced surges exert a considerable influence on the shore processes; the height and geomorphological importance of the surges increase northward.

Comparison of space images taken at different time shows that remnants of the young terrace dated to 1929 appear completely flooded by the surges and the waves reach directly the base of sea cliff cut into the New Caspian plain. Narrow but prolonged beach ridges fringe the reed-covered mud flat all the way. There is a line of offshore bars at 0.5 to 1 km off the coast, their crests showing above the water; a few of them—near the Bryanskaya Spit and north of it—existed before, but a majority have not been known previously.

The wind-induced surges flood completely the above mentioned Bryansky canal delta which adjoins an inactive cliff. A rather broad permanent lagoon formed at the back of it. The fact suggests that under conditions of the transgression the solid runoff of the canal cannot compensate for rapid rise of the sea level, and the delta progressively goes under water.

The mud flat became notably wider and waterlogging more pronounced at the distal parts of the Bryanskaya and Suyutkina spits. It is typical of the Bryanskaya Spit in particular, as it is surrounded with a gentler offshore slope. The outermost beach ridge of the spit has been already broken through by the wind-induced surges, and the sea water repeatedly fills the former lagoon behind the ridge (1–1.5 km

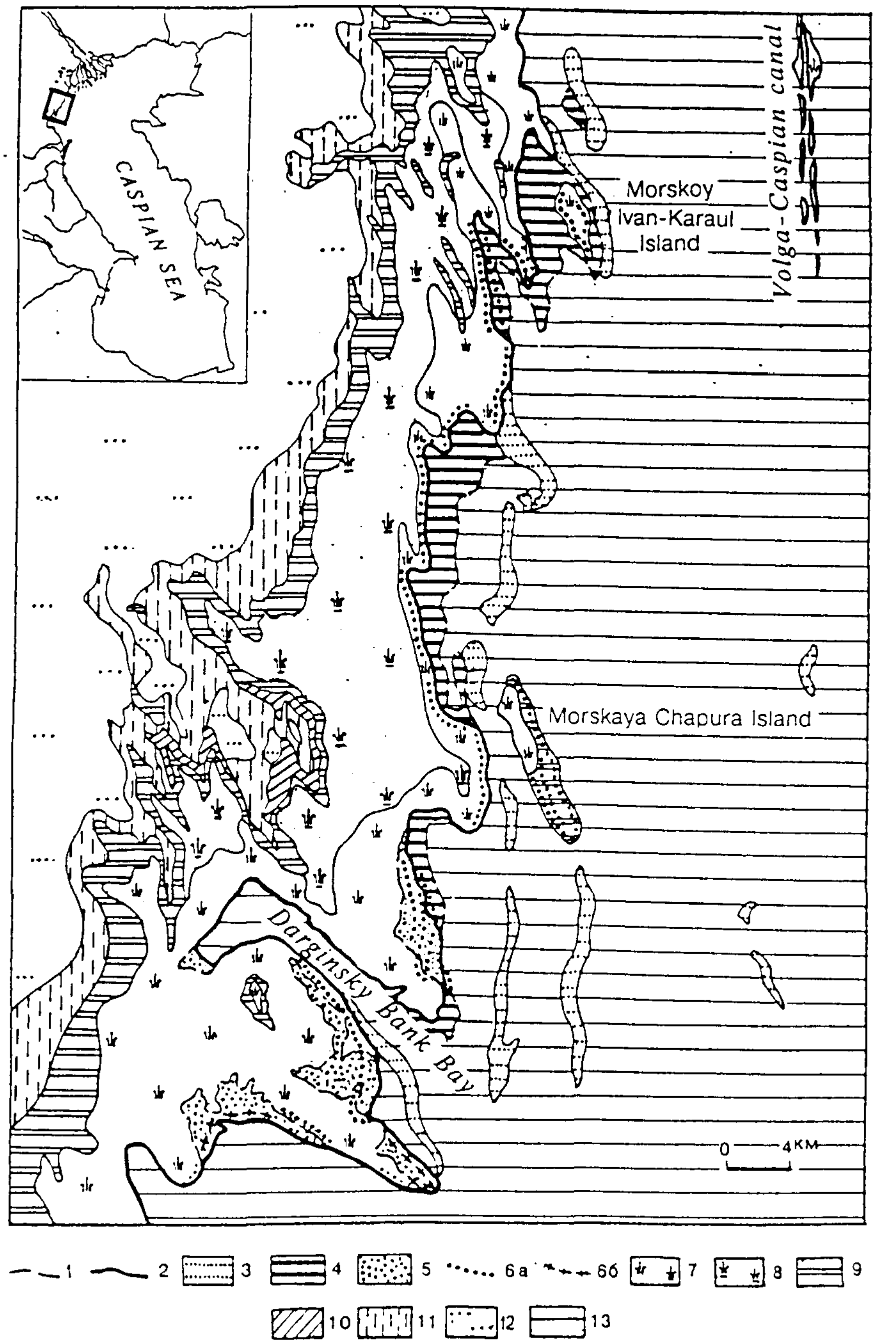

Figure 3. Kalmykian coastal zone, southern part. (1) outer limit of the reed covered and the coastline in 1978; (2) the same, in 1991; (3) submarine constructional landforms (barriers, ridges) eroded by the rising sea; (4) drowned areas of the former reed-covered flat (zone of the coast retreat); (5) sand flat, newly formed (zone of the coast accretion); (6) marine constructional landforms (ridges, barriers) formed: (a) in place of open shallows, (b) in place of the reed-covered flat; (7) areas of the reed-covered flat persisting; (8) areas of reed growth on former land surface (zone of the landward shift of the reed-covered flat); (9) lagoons newly formed at the back of the flat; (10) areas drying during intervals of the wind-induced low sea level; (11) waterlogged zone along the lagoons; (12) land; (13) sea.

wide and about 10 km long). Similar lagoons formed at the back of stadial ridges of the Suyutkina Spit as well. A narrow young beach ridge appeared at its distal end supplied with sediments resulting from the cliffs erosion; the beach ridge fringes the outer edge of the mud flat over a length of 6 km and follows precisely the outlines of the spit. A broad submarine constructional platform protrudes now as far as 1 to 3 km off the shoreline—that is a good evidence for de-

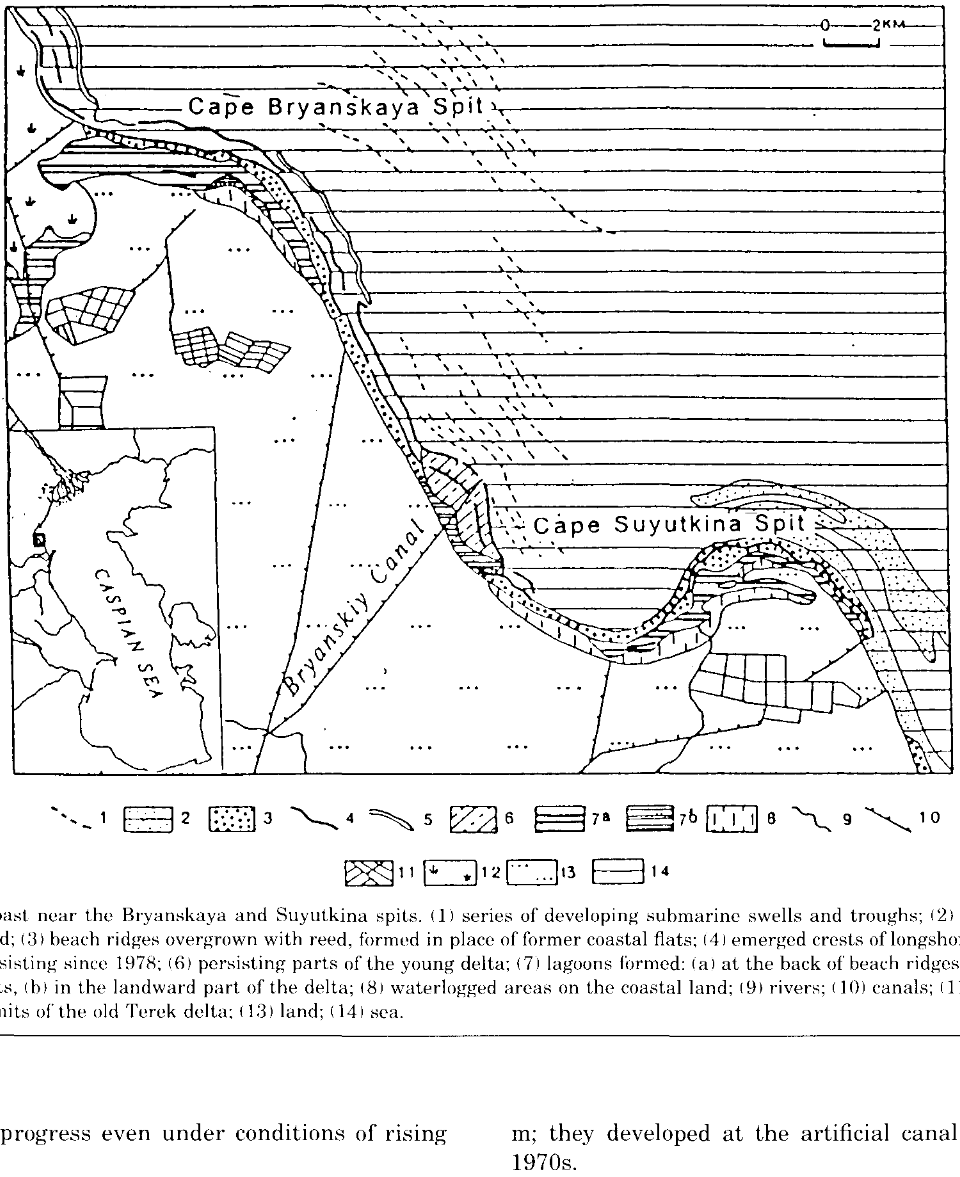

Figure 4. Caspian coast near the Bryanskaya and Suyutkina spits. (1) series of developing submarine swells and troughs; (2) submarine wave-built platform, newly formed; (3) beach ridges overgrown with reed, formed in place of former coastal flats; (4) emerged crests of longshore bars, newly formed; (5) longshore bars persisting since 1978; (6) persisting parts of the young delta; (7) lagoons formed: (a) at the back of beach ridges belonging to different generations of the spits, (b) in the landward part of the delta; (8) waterlogged areas on the coastal land; (9) rivers; (10) canals; (11) rice fields; (12) reed swamps within the limits of the old Terek delta; (13) land; (14) sea.

position being in progress even under conditions of rising sea level.

Thus, the recent dynamics of the coastal stretch south of the Kizlyar Bay is distinguished by still active deposition and erosion, the latter growing in importance. The trend is expected to persist if the sea level rise continues.

The Former Terek Delta Coast South of the Suyutkina Spit

For decades, this stretch (Figure 5) provided the Suyutkina Spit with sediments which came from wave erosion of low (1 to 3 m) cliffs which cut both in the base of the spit itself and lobes of the former delta of the Terek. During the preceding regressive stage, this sector featured straightened erosional coast, though the marine erosion processes were weakened during the maximum of sea regression and acted only at time of wind-induced surges. Almost continuous zone of reed-covered flat about 1 km wide fringed the coastline. From the straight line of the coast small deltas protruded as far as 100 m; they developed at the artificial canal mouths in 1960–1970s.

The recent rise of the sea level led to general flooding both of the deltas and narrow flats. As a result, sea cliffs have been reactivated, though we cannot obtain quantitative estimates of the coast recession from the space images. Under conditions of the recent transgression the system of submarine bars following the coastline is subjected to some transformations. The photo interpretation reveals as many as 4 series of submarine bars within individual stretches of the coast (where new bars added to old ones).

On the whole, the processes of marine erosion typical of this coastal sector have been aggravated by the rising sea level.

The Agrakhan Peninsula

Originally, the peninsula is a sediment barrier which later acquired characteristics of a free constructional landform (spit) fed by longshore drift of sediments (LEONTYEV and

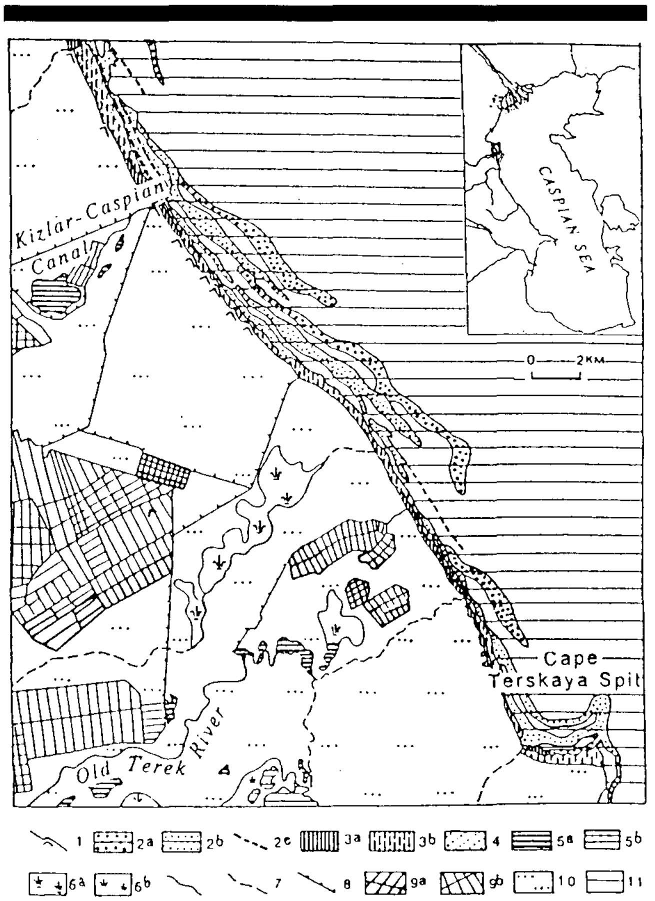

Figure 5. The Terek delta coast south of the Suyutkina spit. (1) coastal casps formed near mouths of canals, streams and distributaries since 1978; (2) submarine longshore bars: (a) newly formed, (b) persisting, (c) recorded in 1978 but not found in 1991; (3) reed growth on shallows: (a) persisting, (b) recorded in 1978, destroyed by 1991; (4) plumes of fluvial sediments; (5) inner water bodies: (a) newly formed, (b) persisting; (6) reed swamps in delta: (a) newly formed, (b) persisting; (7) rivers, intermittent streams; (8) canals; (9) rice fields: (a) newly formed, (b) persisting; (10) land; (11) sea.

KHALILOV, 1965). It is the largest Holocene marine feature within the Caspian Sea basin. During the regressive sea stage, it was fringed by beaches of sand and shells. An altitudinal aerial photo taken in 1978 shows a broad band of wet beaches with a succession of narrow beach ridges. Only at the northern extremity of the Agrakhan Spit, reed-covered mud flats developed around small-sized sandy islets separated by channels. Bare sandy-mud flats fringed the peninsula coast facing the Agrakhan Bay.

In the late 1950s, after the Sulak mouth was artificially moved southward, the sediment supply to the Agrakhan Spit reduced drastically which resulted in erosion of its base at a rate up to 10 m per year (LEONTYEV *et al.*, 1977). By the outset of the sea transgression, however, (that is, in 1978–1979) the sector appeared in the wave shadow, in the lee of a young spit actively growing from the former Sulak delta, and the erosion practically stopped.

Mud flats still continued to form at the distal part of the Agrakhan Spit, because sediments were supplied there by the new mouth of the Terek artificially diverted in 1973 towards the marine side of the Agrakhan Peninsula (the construction was intended for emergency discharge of river flood water). A quickly growing delta at the new mouth interrupted otherwise the straight coastline of the Agrakhan peninsula.

A rise of the sea level since 1978 produced essential changes in the peninsula coasts (Figure 6). A space photo taken in 1991 clearly shows the reed-covered mud flat being partly flooded on its eastern and northern coasts, where the coastline retreated up to 1 km. At present the coastal zone of the whole peninsula and that of the Chechen Island feature a narrow barrier bar which is consistent with a well known model of the coastal zone response to the sea level rise (IGNATOV *et al.*, 1989, 1993). Sea waves swash over the barrier; this process, together with a rise of the ground-water table, accounts for a narrow lagoon being formed behind the barrier.

On western coast of the peninsula a series of large eolian blowouts are filled with water, while all of them were dry in 1978.

Considerable changes occurred in the "newly formed" delta of the Terek. In 1978 it just began to form after a cutoff across the Agrakhan Peninsula had been open in 1977. At the outset of the sea transgression the delta was less than 0.5 km^2 in area and was prograding into the sea at a rate 0.3 to 0.4 km/year. In spite of the sea level rise, the delta continued to grow, and by September 1987 it extended 1.4 km from the coast, its area being as large as 3.2 km^2 (MIKHAILOV and MIKHAILOVA, 1991). Later on, however, the deltaic sedimentation could not compensate for the sea level rise which resulted in the delta area reduction—low coasts were flooded, lagoons increased in width, and the seaward edge of the delta underwent erosion.

In case the sea level rises as high as −25 to −26 m, the new Terek delta would be submerged completely, and the whole coastline of the peninsula would migrate landward. It is likely that the proximity of the Agrakhan Spit would be actively eroded after submergence of the mentioned above spit which protected it in 1991–1992 (the time of our last space pictures).

The Sulak Delta

The cuspate delta of the Sulak River protrudes conspicuously at the base of the Agrakhan Peninsula. Due to dominance of southeasterlies, the delta is somewhat deflected northward and on the whole extends north–south. In the middle of the century the northern edge of the delta was prograding into the sea at a rate of 100–200 m yearly (LEONTYEV *et al.*, 1987), separating the Sulak Bay. In 1957 lower stretch of the Sulak River was artificially straightened in order to promote flood water discharge thus avoiding catastrophic floods in its valley. The canal diverted the river flow southward and captured the principal portion of the sediments; as a result, a new delta began to form actively south of the former one. Under conditions of insufficient sediment supply, the seaward edge of the former delta was exposed to wave erosion which began even before the sea level rise. The products of

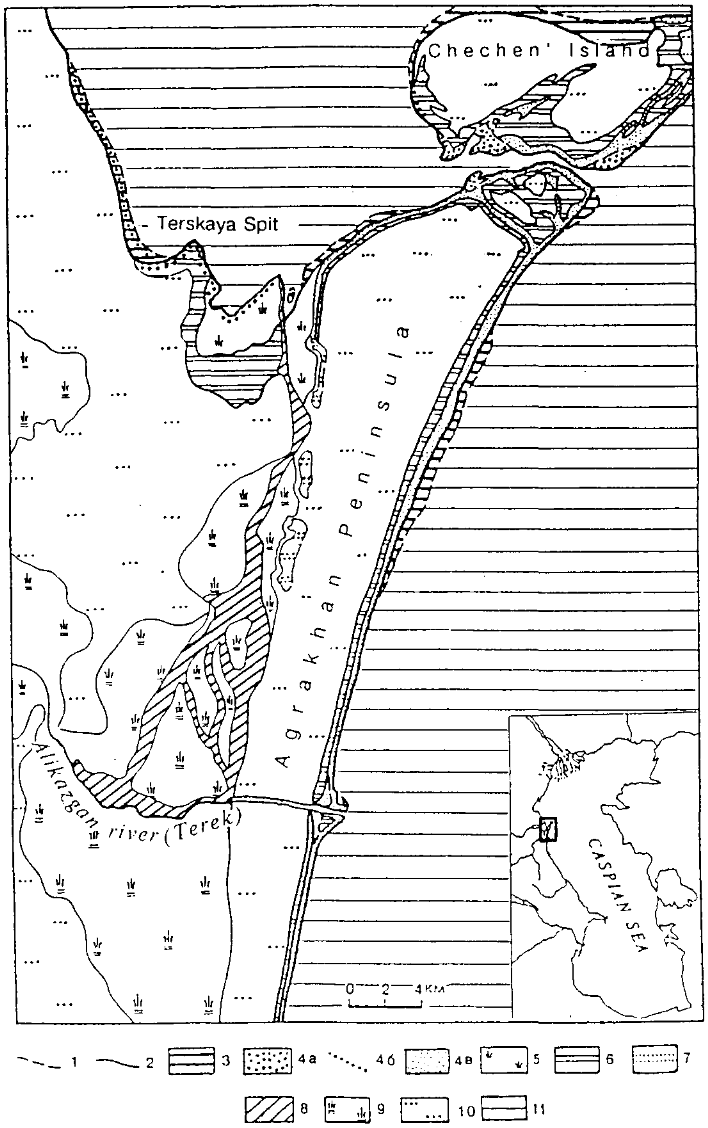

Figure 6. The Agrakhan Peninsula. (1) coastline in 1978; (2) coastline in 1991; (3) drowned areas of the former reed-covered flat (zone of the coast retreat); (4) beach ridges and barriers overgrown with reed: (a) formed on open shallows, (b) formed within sectors of the coast retreat, (c) on drowned beaches and marine terraces; (5) reed-covered flat, persisting; (6) lagoons formed in place of beaches and marine terraces; (7) wind-blown hollows filled with water; (8) areas of deltaic deposition along the Terek old channel (reed-covered levees); (9) reed swamps with small areas of open water within the old delta of the Terek; (10) land; (11) sea.

erosion were transported towards the northern margin of the old delta where a narrow and long (up to 5 km) spit developed. The spit almost completely detached the Sulak Bay from the sea and acted as a wave breaker of a sort protecting the base of the Agrakhan Peninsula from the wave erosion.

The recent sea level rise radically altered the situation on the coast (Figure 7). The most important change is that more than a half of the old Sulak delta together with the young spit at its northern end were submerged, as well as low coasts of the Sulak Bay. As a result, the sea appeared dangerously close to the Sulak village. After the young northern spit went under water, the waves approach unobstructedly the base of the Agrakhan Peninsula where processes of coastal erosion reactivate. The latter are somewhat retarded by a narrow barrier bar about 4 km long formed within a shallow part of the flooded old delta of the Sulak River.

The young delta of the Sulak River was also modified by 1991 as the sediment supply can no longer compensate for the sea level rise. Besides, the river flow backup resulted in a detectable reduction in the sediment load. As a consequence, the sea actively advances onto the delta, the whole its distal part being drowned. At the back of the delta, two broad (0.5 to 0.8 km) lagoons appeared, detached from the sea by narrow barrier bars.

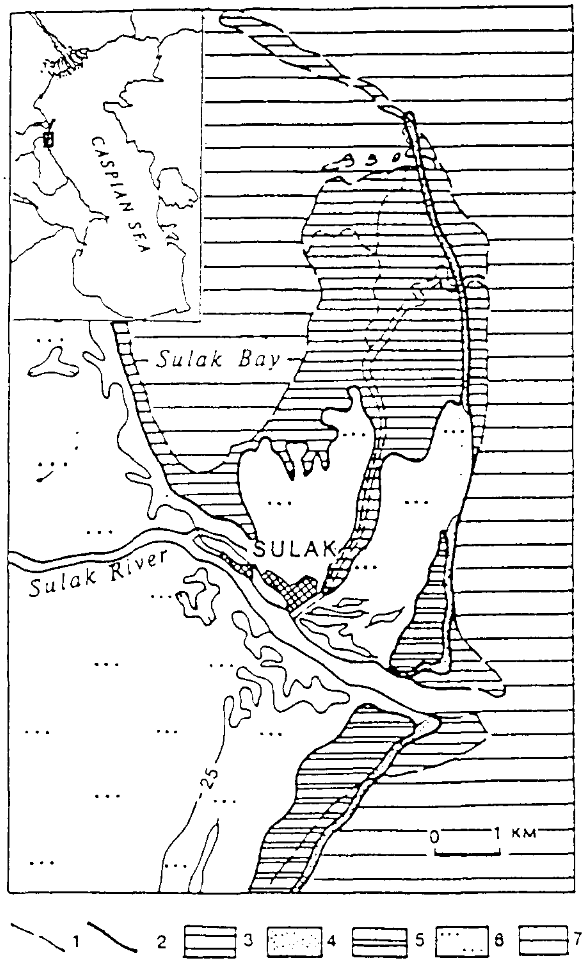

Figure 7. Delta of the Sulak River. (1) coastline in 1978; (2) coastline in 1991; (3) flooded parts of the delta; (4) constructional landforms (beach ridges, bars) on the flooded delta surface; (5) the present-day lagoons; (6) land; (7) sea.

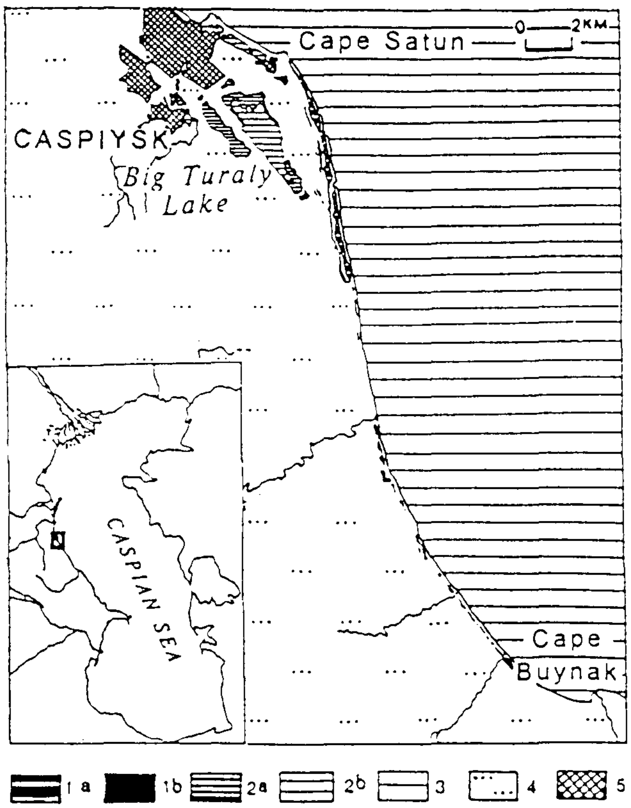

Figure 8. Daghestan coast near the city of Caspiysk. (1) newly formed lagoons: (a) filled with water, (b) swampy and overgrown with reed; (2) lakes: (a) newly formed, (b) persisting; (3) sea; (4) land; (5) urban area.

In case the sea level continues to rise, both old and newly formed deltas will be continuously eroded and flooded. At a sea level at −25 m, not only the newly formed delta but almost the whole surface of the old delta would be drowned, the territory of the Sulak village included. The backed-up river water is likely to flush into the Sulak Bay.

The Daghestan Coast Near the City of Caspiysk
(Figure 8)

Before the outset of the recent marine transgression, this stretch of the coast (between the city of Caspiysk and the Buynak Cape) was distinguished by wide (up to 150 m) sandy beaches fringing young regressive terraces formed in 1929 and 1941. The terraces formation prevented the coast from erosion and a majority of cliffs became inactive. A space photo taken in 1991 clearly shows that the recent sea level rise led to almost complete submergence of the young terraces. The water edge came up to the former cliff base and this induced their reactivation. The coast near Caspiysk and Manas is known to suffer from severe erosion at present. The small-scale space photos do not allow, however, to trace the process in detail.

Transgressive changes of the coastal morphology are better seen on lower depositional stretches. A large beach ridge 1.5 to 2 m high is usually formed near the water edge, with lagoons at the back of it; the lagoons are fed by storm waves swashing over the ridge as well as by groundwater, which raises its table along with the rise of the sea level. Such a lagoon, about 10 km long and 200–300 m wide, is located to the southeast of Caspiysk. Further landwards, a number of old dry depressions—former lagoons—show a distinct increase in humidity, with reed swamps newly formed on their floors. A chain of such waterlogged lagoons follows the coastline almost to the Buynak Cape.

A certain increase in moisture supply is noticeable farther away from the coast. Thus, the Bolshie Turali Lake increased its area, and a formerly dry depression west of the lake has been filled with water.

The Daghestan Coast Near the Adji Lake (Figure 9)

Interpretation and comparison of high altitude aerial photos taken in 1979 and satellite imagery dated to 1991 have shown coastal changes within this sector much alike to those

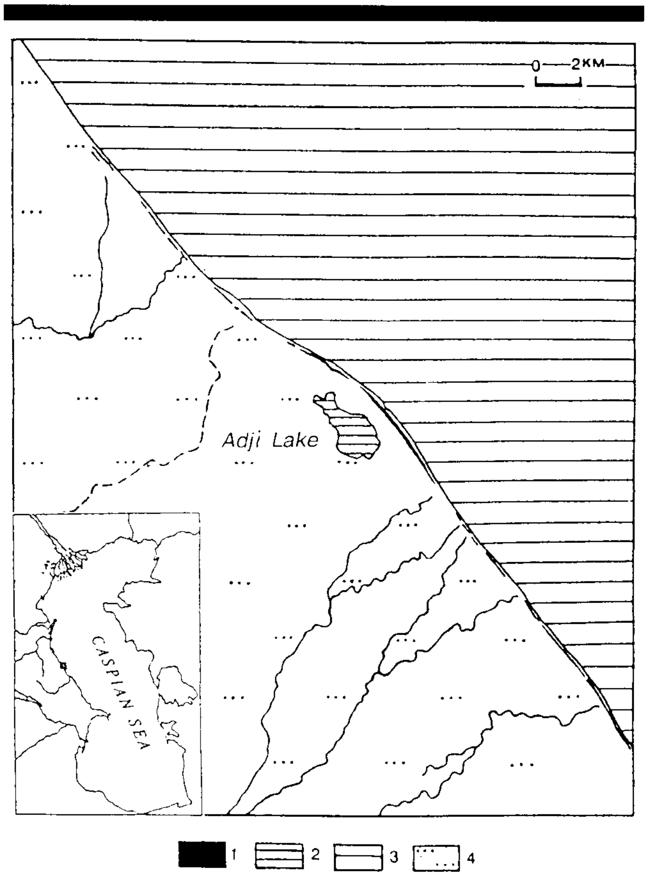

Figure 9. The Daghestan coast near the Adji Lake. (1) newly formed lagoons; (2) lakes; (3) sea; (4) land.

discussed above. As is the case of the Caspiysk sector, depositional stretches are interspersed with active cliffs, and the dynamics of the latter cannot be traced in small-scale space photos. The most characteristic feature of the depositional stretches is a chain of back-barrier lagoons filled with water. Narrow elongated lagoons run the whole length of the coast (with a few interruptions); their width does not exceed 100 m, with the exception of the largest depositional stretch near the Adji Lake where the lagoons are as broad as 200 m.

CONCLUSIONS

The comparative analysis of the high-altitude aerial and space photographs taken at the time of the sea regression (mostly, in 1977–1978) and during the sea transgression (1982–1986 and 1991–1992) shows that the imagery may supply useful additional data about changes within the coastal zone under conditions of rising sea level; the information is of general character and may cover large sectors of the coast. On the whole, the interpretation results indicate that the effect of the Caspian Sea level rise becomes more pronounced from north to south, as the offshore slope increases its gradients and depositional coasts give way to erosional ones. It appeared very difficult to trace quantitatively marine erosion from the small-scale images, even though it becomes gradually extremely dangerous, within urban areas in particular. The changes, however, are distinctly seen along the flat coasts where the sea level rise results in a considerable landward shift of the coastline.

They are most conspicuous in the northern half of the coast, where the zone exposed to the rising sea effects is up to a few kilometers wide; the exception is the northernmost sector adjoining the Volga prodelta which attenuates the influence of the recent sea transgression. In the northern part, a majority of flat coasts appear flooded and the shore profile is somewhat remodelled by waves (*e.g.* a series of beach ridges are forming near the water edge); lagoons develop at the back of mud flats, and the whole mud flat complex is shifted landwards. Passive flooding by sea water has been recorded only in distal parts of large depositional landforms (spits, deltas).

The southern part of the Caspian coast of Russia is distinguished for more steep offshore zone, the principal transgressive modifications are limited there to a rather narrow strip (a few kilometers wide). The shore profile is actively remodelled by waves, in agreement with the model of coastal response to the sea level rise (Ignatov *et al.*, 1987, 1993); the model forecasts erosion of sea cliffs within steep stretches and formation of a large barrier bar with a broad lagoon at the back of it on flat coasts. The latter case is well seen in space imagery of the coasts from Caspiysk City to the Buynak Cape.

The described changes in the coastal zone along the Caspian coast of Russia have been identified in 1991–1992, when the photographs were taken. The changes, however, continue along the same lines at present, as the sea level is still rising.

The results discussed above permit to recommend comparative analysis of aerial and space photoimages taken at different time for monitoring of the Caspian coasts as an expedient means for control of the state of coastal environment for planning of practice measures of coastal protection and for economic development under conditions of the sea level fluctuations.

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