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Quaternary river terraces as indicators of the Northwestern Caucasus active tectonics

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The Northwestern Caucasus has been developing at the periphery of the collision zone of the Scythian Plate and Georgian Massif. Study of the Quaternary terraces of the largest mountain rivers, flowing across the folded ridges and depressions, is one of the main sources for the estimation of the uplift rate of active tectonic structures. Remote sensing, field geodesy, tectonophysics, palaeontological and archaeological studies, as well as the correlation of river terraces with known and well-dated marine terraces, have provided new data on the age of river terraces. These data have made it possible to estimate the age of tectonic deformation and the uplift rate of active folded and faulted structures. These deformations are directly expressed in the topography of the area, and continue to evolve under conditions of contemporary lateral compression predominating in the Northwestern Caucasus. The field data provide evidence of the beginning of deformation and uplift, which started at the end of the Middle Pleistocene and later accelerated during the Late Pleistocene-Holocene time.

1. Introduction

The Northwestern Caucasus (NWC) is the lowland periclinal segment of the folded system of the Great Caucasus. It has been developing on the periphery of the collision zone of the epi-Hercynian Scythian Plate and Georgian Massif. The GPS velocities confirm weak general compression of the mountain system of the Great Caucasus with a maximum rate of about 1–2 mm/year (Milyukov et al., 2015). Among current tectonic models explaining the compression of the Greater Caucasus, two main should be noted. The first one assumes underthrusting of the Georgian Massif beneath the Scythian Plate (Dotduev, 1986; Philip et al., 1989; Khain et al., 2006; Popkov, 2006, 2007 and other). It is verified by the distribution of deep earthquakes (Mumladze et al., 2015). The second one implies compression and linearization of folded structures and denies a low-angle detachment at the base of the collisional Caucasus orogeny (Rastsvetaev et al., 2010). It corresponds to vertical tectonic zonation of the mountain building deep structure (Rogozhin et al., 2015; Shempelev et al., 2017). The results of this paper do not contradict with both of these models and do not allow to give preference to any of them.

The history of the tectonic development of the region is reflected in its topography. Low and middle-mountain folded ridges and depressions prevail in the NWC. Their structure becomes more complicated in the southeastern direction successively, while the age increases. Active orogenic movements in the axial zone of the NWC started not earlier than the Tortonian-Messinian age (Milanovsky, 1968). During the Pliocene they spread to the northern and southern foothills and in the Quaternary period they reached the Taman Peninsula (Borukaev et al., 1981; Nesmeyanov and Izmailov, 1995; Trifonov, 1999; Izmailov, 2007).

The purpose of this article is to determine active tectonic structures of NWC, expressed in topography, directions and rates of their development in the Late Quaternary time by studying the tectonic deformations of the terraces of the largest river valleys. Identification and investigation of Quaternary development of such morphostructures have become possible in the Sochi model area of the NWC. The structures inherited from the main stage of the folding and newly formed ones have been studied.

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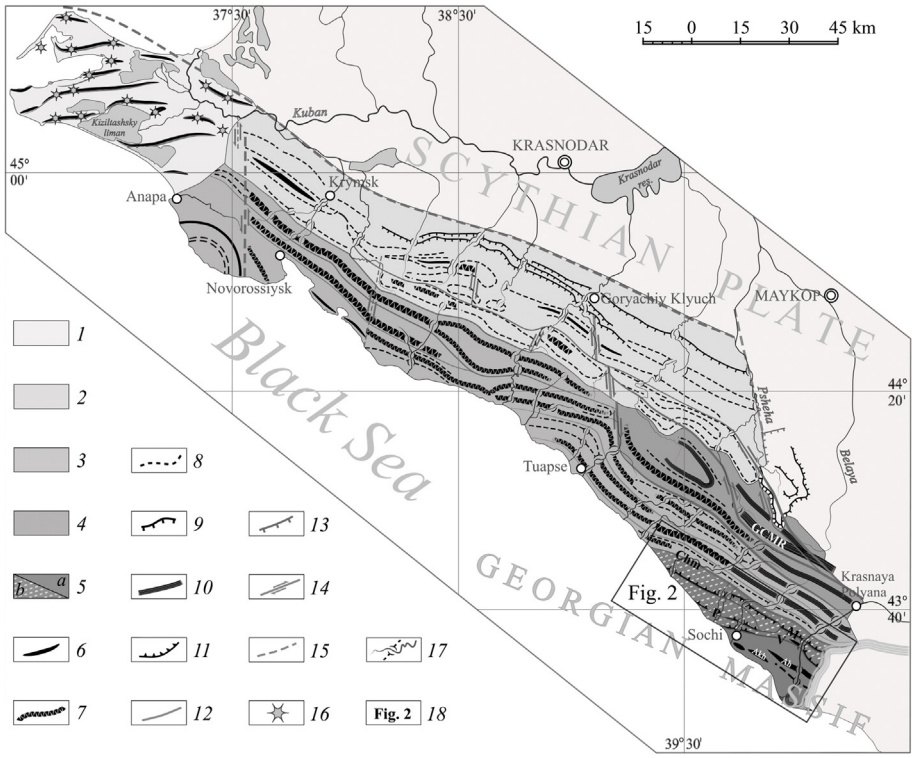

Fig. 1. The morphotectonic map of the NWC (Trikhunkov, 2016). 1–5 – morphotectonic areas: 1 - Taman, 2 – Abino-Gunaisky, 3 – Novorossiysko-Lazarevsky, 4 – Goytkh 5 – Sochi (a – Adler subarea, b – Plastunka subarea); tectonic landforms: 6–9 - ridges: 6 - anticline, 7 - condenudation syncline, 8 - condenudation homocline, 9 - cuestas, 10 - folded-block, 11 - fold-thrust; 12–15 - faults: 12 - thrusts, 13 - reverse, 14 - strike-slip, 15 - inferred; 16 - mud volcanoes; 17 - rivers and canyons; 18 - Fig. 2 location. Letters: Akh – Akhun, Ah – Ahshtyr, GCMR – The Main Caucasian Ridge; thrusts: Chm – Chemitokvadge, M – Monastery, P – Plastunsky, V – Vorontsovsky.

2. Regional setting

The NWC is divided into five morphotectonic areas that differ in their tectonic structure, age, topography and modern geodynamics (Fig. 1). They are Taman, Abino-Gunaysky, Novorossiysk-Lazarevsky, Goytkh and Sochi areas (Trikhunkov, 2008, 2010, 2016). The last one corresponds to the margin of the Georgian Massif, which expands to the Black Sea basin, becoming the Shatsky Ridge (Ershov and Nikishin, 2004; Khain et al., 2006). Having the largest river valleys in the region with the most complete terrace series available for research, Sochi morphotectonic area was chosen as the region of study.

In this study, Sochi area has been divided into Adler and Plastunka subareas, which have a different morphotectonic style (Figs. 1 and 2). The southern part of the Georgian Massif is not covered by allochthonous structures, and here the initial folded deformations of the young sedimentary cover are presented. These tectonic features are expressed in the original style of morphostructure and allow to distinguish Adler morphotectonic area. The anticlinal ridges (Ahshtyr, Monastery, Akhun, Bytkha), as well as homoclinal Verhnenikolaevsky ridge, have general Caucasus strike. (Fig. 2). The limbs of the folds consist of clay, siltstone and sandstone of the Lower Oligocene, while the folded cores are made of the Upper Cretaceous limestone and marl. These ridges are separated by syncline and homocline depressions filled with terrigenous rocks of the Middle-Upper Oligocene with prevailing clay, silt and sandstone. Imereti depression is filled with Neogene clays with layers of sandstone and conglomerates as well as Quaternary pebbles and sands.

In the basement of the adjacent Plastunka subarea the largest allochthonous structure of the region, Vorontsovsky nappe, lies. It has been squeezed out from Chvizhipse folded zone (Dotduev, 1986) – part of the Novorossiysk-Lazarevsky zone (Figs. 1 and 5). The nappe is composed of the Paleocene-Eocene terrigenous sediments with prevailing sandstone and marl and is expressed in the relief of the Plastunka depression (Fig. 2). In the north the depression is bordered by the Monastery thrust, which is the boundary between Chvizhipse folded zone and the Georgian Massif. The described structure is the basement of the Alek ridge. Plastunsky thrust and Vorontsovsky overthrust form the boundary of the depression in the south. Mamaika and Navaginka ridges were formed within the frontal zone of these structures (Fig. 2). The total southward displacement of the Vorontsovsky nappe is at least 15 km (Sholpo et al., 1993; Yakovlev et al., 2008).

3. Methods

The principal method of the study is a morphotectonic analysis of geological maps, satellite imagery and digital elevation models (DEM). Multispectral satellite imagery Landsat-8/OLI (spatial resolution 15 m), QuickBird (spatial resolution 2.5 m) and stereo imagery KH-9 Hexagon (spatial resolution 4 m) have been interpreted. Altitude data have been derived from the ASTER global DEM (spatial resolution about 30 m). The Geological Map of the Russian Federation, Series Caucasus, scale 1:200 000 (sheet K-37-IV, sheet L-37-XXXIV, with Explanatory note) (State Geological Map …, 1999) serves as an important source of geological data.

Detailed morphotectonic classification, conducted previously, has allowed creating of a morphotectonic zoning map of the NWC, scale 1:500000 (Fig. 1) with five morphotectonic areas (Trikhunkov, 2016). The zoning is based on the prevailing linear folding under lateral stress in the region (Trifonov, 1999; Ershov and Nikishin, 2004; Khain et al., 2006; Popkov, 2006, 2007, Trikhunkov, 2008, 2010, 2016). A different concept of the morphotectonic zoning based on contrast vertical block movements is offered in the papers of Milanovsky (1968), Rantsman (1985), Nesmeyanov (1992), Nesmeyanov and Izmailov (1995). The study of the area have resulted in morphotectonic schemes and profiles of the largest valleys, the basic morphometric parameters of their terraces with the accuracy of ca. 5 m have been measured.

Deformation of the largest river terraces of the Caucasian Black Sea coast is the significant evidence of active tectonics of the region. Detailed description and correlation of the terrace series of the Mzymta and Sochi rivers, based on the published data, satellite imagery interpretation, survey of geomorphological positions and sedimentary sections, have been performed. The middle and lower parts of the valleys of the rivers were covered by a network of longitudinal and transverse sections. The sites with the most complete set of the terraces on one cross-section of the valley and areas of inferred tectonic deformations

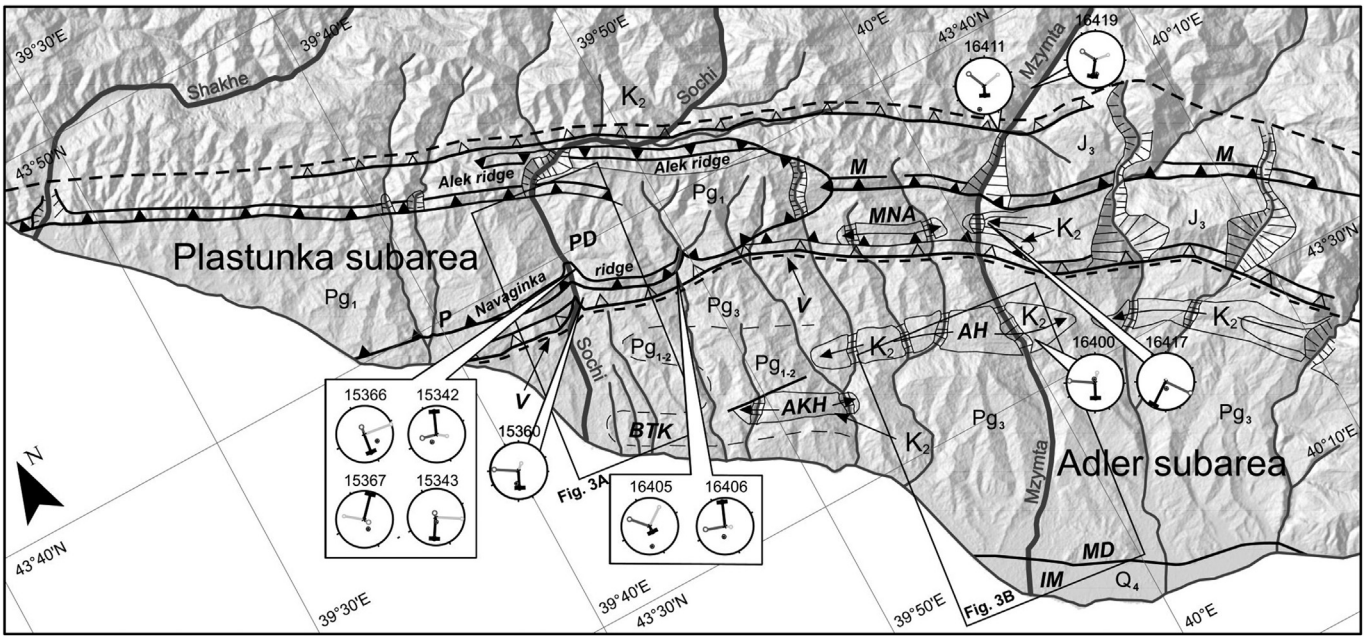

Fig. 2. Structures of Sochi areas, shown on hillshaded ASTER GDEM. Dashed lines are limits of Adler and Plastunka morphotectonic subareas. Faults are shown with solid lines, solid teeth for thrusts, open teeth for overthrusts, teeth in direction of dip. Fault ridges are indicated with an underlined symbol of fault; anticline ridges are shown with a double-sided arrow along the axis and outlined with a thin line; antecedent valleys are hatched. Indices of structures are shown in bold italic: AKH - Akhun anticline, AH - Ahshtyr anticline, BTK - Bytkha anticline, IM - Imereti depression, MD - Moldovka flexure, MNA - Monastery anticline, M - Monastery thrust, P - Plastunsky thrust, PD - Plastunka depression, V - Vorontsovsky overthrust. Indices of geological systems and series are shown in bold. Stereoplots of local stress (lower hemisphere) are labelled with sampling indices; black axis with a dash at the end, maximal principal stress; dark grey axis, intermediate; light grey axis, minimal; 'x' mark, poles of bedding planes. Compiled using State Geological Map of the USSR (State Geological Map …, 1964) with changes.

have been surveyed. In these sites levelling was performed with a hand level while in some cases the data of field levelling were supplemented by DEM-derived profiles. Thus, the terraces have been traced from the mouth 18 km inland to the Monastery village in the Mzymta river valley, 16 km inland to the foot of the Alek ridge in the Sochi river valley. The river terraces have been further correlated with well-studied marine terraces (Scheglov, 1986; Nesmeyanov, 1992; Nesmeyanov and Izmailov, 1995; Trifonov, 1999; Izmailov, 2007; Nikiforov and Kozhurin, 2011; State Geological map …, 1999; Ob'yasnitel'naya zapiska …, 2010; Yanko-Hombach et al., 2011; Trikhunkov et al., 2015). Therefore, the age of the marine terraces has become the main source to estimate the age of the river terraces, which are usually considered to be cyclic fluvial terraces, created by erosion-accumulation succession of glacial and interglacial periods. The names of the marine terraces correspond to the common Black Sea scale while the names of the river terraces are given according to the Geological Map of the Russian Federation, Series Caucasus (State Geological map …, 1999). Correlation of the studied terraces with marine isotope stages (MIS) is shown in Table 1.

The samples of terrace material were collected for fauna and pollen investigations. However, only some fragments of the shells of bivalve marine molluscs (central parts of the valves) of the family *Veneridae* have been found. They seem to be modern according to the degree of preservation, and probably brought by birds.

14 pollen samples have been collected from the floodplain facies of terrace sections. The combination of Grichuk's and Fagri-Iversen's methods has been used to enrich the samples (Rudaya, 2010; Fagri and Iversen, 1989). The obtained samples have been examined under the Zeiss Axiostar microscope at × 400 magnification and by comparing the yield to the reference pollen collections of the Institute of Geography RAS (Moscow) and to the respective photo atlases (e.g., Reille, 1992; Beug, 2004).

Archaeological sites of the Middle-Upper Palaeolithic described in the region (Baryshnikov, 2012; Kulakov et al., 2007; Kulakov and Pospelova, 2012; Shchelinsky, 2007) have provided additional data for the river terraces dating.

Another approach of studying active tectonic deformations is the measurement of tectonic fractures, faults and offsets on them. Data on the geological stress indicators (slickensides, tension gashes, minor faults and joints) have been obtained in the field. The field data have been processed using algorithms and software (STRESSGeol programme (Rebetsky et al., 2012)) of Tectonophysics Laboratory of The Schmidt Institute of Physics of the Earth of the Russian Academy of Sciences (IPE RAS) to determine the tectonic stress parameters.

4. Results

4.1. Fluvial terraces

Terrace series have been traced upstream from the mouths of the largest rivers in the region – the Mzymta and the Sochi. Six terraces have been investigated: Pavlovskaya (II), Popovskaya (III), Pugachevskaya (IV), Partizanskaya (V), Izumrudnaya (VI), Rodnikovaya (VII) (State Geological map …, 1999). Due to the sea level increase after deglaciation the youngest terrace (I) appeared to be inundated (the rate of continental uplift was lower than the rate of sea water level increase). Thus, the youngest alluvial deposits of the New Euxinian and Chernomorskaya (Holocene, MIS 1) transgressions are not exposed (For details see Table 1). According to borehole data, New Euxinian (aI) estuarian loam in Imereti depression was described at the depth of 80 m and has the age 10.488 ± 2.53 ^{14}C cal. ka BP (MIS 1) (State Geological map …, 1999). Thus, the terraces below Pavlovskaya terrace 5–8 m high (equal to Sochi marine terrace) have not been found out in the Mzymta and Sochi valleys. In this paper traditional indexing is used and New Euxinian age deposits have been identified as the first river terrace deposits to avoid misunderstanding (Table 1).

Sedimentary sequences of the Pavlovskaya (II), Popovskaya (III), Pugachevskaya (IV) and V Partizanskaya (V) terraces have been studied. All the terraces have similar constitution: coarse-grained channel alluvium covered by fine-grained floodplain alluvium at the top (for

Table 1
Correlation of river and marine terraces of Sochi morphotectonic area (marine isotope stages provided for reference).

Terrace №	River terrace (with conventional index)	Marine terrace (with conventional index)	Age (ka), UTh - uranium-thorium, TL – thermoluminescence dating	Surface height above river in its mouth (meters)	Alluvium thickness (meters)	MIS	NW European stages
II	Pavlovskaya (aII)	Sochi marine (mII)	Corresponds to the Bryansk inerstadial	5–8	2 - 3 to 6 - 8	3	Denecamp inerstadial within Weichselian
III	Popovskaya (aIII)	Early Agoy ($mIII_2$) Late Agoy ($mIII_1$)	48,6; 55,9; 53,2 (UTh) 33,6 ± 0,57 and 35,1 ± 1,2 (UTh)	28–35	10		Weichselian
IV	Pugachevskaya (aIV)	Shakhe (mIV)	74-76 (UTh)	45–50	20–25	5a	Early Weichselian (Odderade) interstadial
V	Partizanskaya (two levels are distinguished) (aV_1 and aV_2)	Early Ashe (mV_2) Late Ashe (mV_1)	from 118 ± 3,5 to 124 ± 3,5 (UTh) 112 (TL)	48–60	2 - 3 to 8 - 12	5e	Eemian
VI	Izumrudnaya (aVI)	Early Uzunlar (mVI)	from 339 to 419 (TL).	68–78	2–6	10–11	Holsteinian to Early Saalian
VII	Rodnikovaya (aVII) (two levels are distinguished)	Vulan (mVII)	Early Neo-Pleistocene (Early Euxinian transgression)	75 - 80 and 85 - 90	1 - 2 to 10 - 12	17–19	Early Cromerian complex

details see Fig. 4). Coarse-grained alluvium appeared to be barren in terms of palaeontological finds (pollen, malacofauna) or materials for ^{14}C dating. The sediments of Izumrudnaya (VI) and Rodnikovaya (VII) terraces are not exposed at the surface, thus they were considered only as geomorphological levels.

The *Pavlovskaya terrace (aII)* is found both in the Sochi and Mzymta river valleys and is traced 15 km inland from the shoreline. In terms of age it can be correlated with the Sochi marine terrace. It is 5–8 m high and is constituted by coarse-grained alluvium (4–6 m thick) covered with flood-plain fine-grained sediments (up to 2–3 m thick). From the seashore towards the inland the fill terrace turns into strath terrace due to tectonic uplift. There is no direct data on the age of the II Pavlovskaya terrace. U-Th-dating of the more ancient III Agoy marine terrace (correlative to the III Popovskaya river terrace (see further)) corresponds to Leningrad interstadial, thus it is likely that the II Pavlovskaya terrace relates to the last episode of Denecamp (Bryansk, MIS 3) mega-interstadial (29–33 ka, Markova et al., 2008). Pollen concentration in these sediments is extremely low. Rare pollen grains of boreal trees with high pollen productivity (*Pinus, Betula, Alnus*) and several herb taxa (Poaceae, Asteraceae, Chenopodiaceae) were identified. This composition of pollen assemblages is not contrary to suggestions that the terrace was formed during the cool interstadial.

The *Popovskaya (aIII)* terrace is found near the lower reaches of the Mzymta, Shakhe and Sochi rivers at an average altitude of 18–22 m. Pebble-boulder deposits with sand-gravel or loam in minor amounts constitute the terrace. The thickness of sediments is no more than 10–12 m and decreases to 3–4 m in tributaries or minor river valleys. All samples for pollen analysis appeared to be barren. Two altitudinal levels of the terrace are distinguished in the Mzymta valley at 28 and 35 m. From the seashore towards the inland the fill terrace turns into strath one due to the tectonic uplift.

The *Pugachevskaya (aIV)* terrace is found in large valleys at altitudes from 45 to 50 m and extends far into the mountains. The most complete sections were described near the Ahshtyr and Plastunka villages (the Mzymta and the Sochi river respectively). The terrace with total thickness of the sedimentary cover up to 15 m thick is composed of boulder-pebble alluvium with interbeds and lenses of clay, sand and conglomerate. Pollen assemblages were characterized by high abundance of boreal trees with broad ecological requirements such as *Pinus, Betula, Alnus*. Pollen of moderate thermophilous taxa *Quercus* and *Corylus* occurred in small amount. Non-arboreal pollen is represented by Poaceae, Asteraceae, Polygonaceae, Ranunculaceae, fern spores of Polypodiaceae were recorded. The composition of pollen assemblages and U-Th-dating of the marine analogue – Shakhe terrace (74–76 ka) shows that the sediments could have been formed during the Early Weichselian (Odderade) interstadial (MIS 5a) (Table 1).

The age of the last two terraces has been confirmed indirectly by archaeological data. The Middle-Late Palaeolithic locality has been discovered on the III and IV terraces in Plastunka settlement by V.E. Shchelinsky (Fig. 3). Tools of the Mousterian type have been collected from the floodplain alluvium facies of the fourth Pugachevskaya terrace and stone artefacts of Upper Palaeolithic appearance have been found in the sediments of the third Popovskaya terrace (Shchelinsky, 2007).

The *Partizanskaya (aV)* terrace has been described in lower reach of the Mzymta and Sochi rivers at altitudes of about 48–60 m and is traced upstream within the entire Sochi morphotectonic area. Deposits with total thickness of 2–12 m constitute two levels and are presented by pebble, boulders, sands and clays. Pollen assemblages were dominated by broadleaf trees, mainly *Quercus* and *Tilia*, with a small amount of *Carpinus, Ulmus, Corylus*. The characteristic feature of pollen spectra is a high abundance of *Prunus* pollen, morphologically close to cherry laurel *Prunus laurocerasus*. Herb pollen is represented by Poaceae, Asteraceae, Ranunculaceae, Caryophyllaceae. These compositions of pollen assemblages are the most thermophilic among the studied samples. Formation of the subaerial part of the outcrop of the terrace with subtropical Colchis flora pollen proceeded under the warmest conditions of the

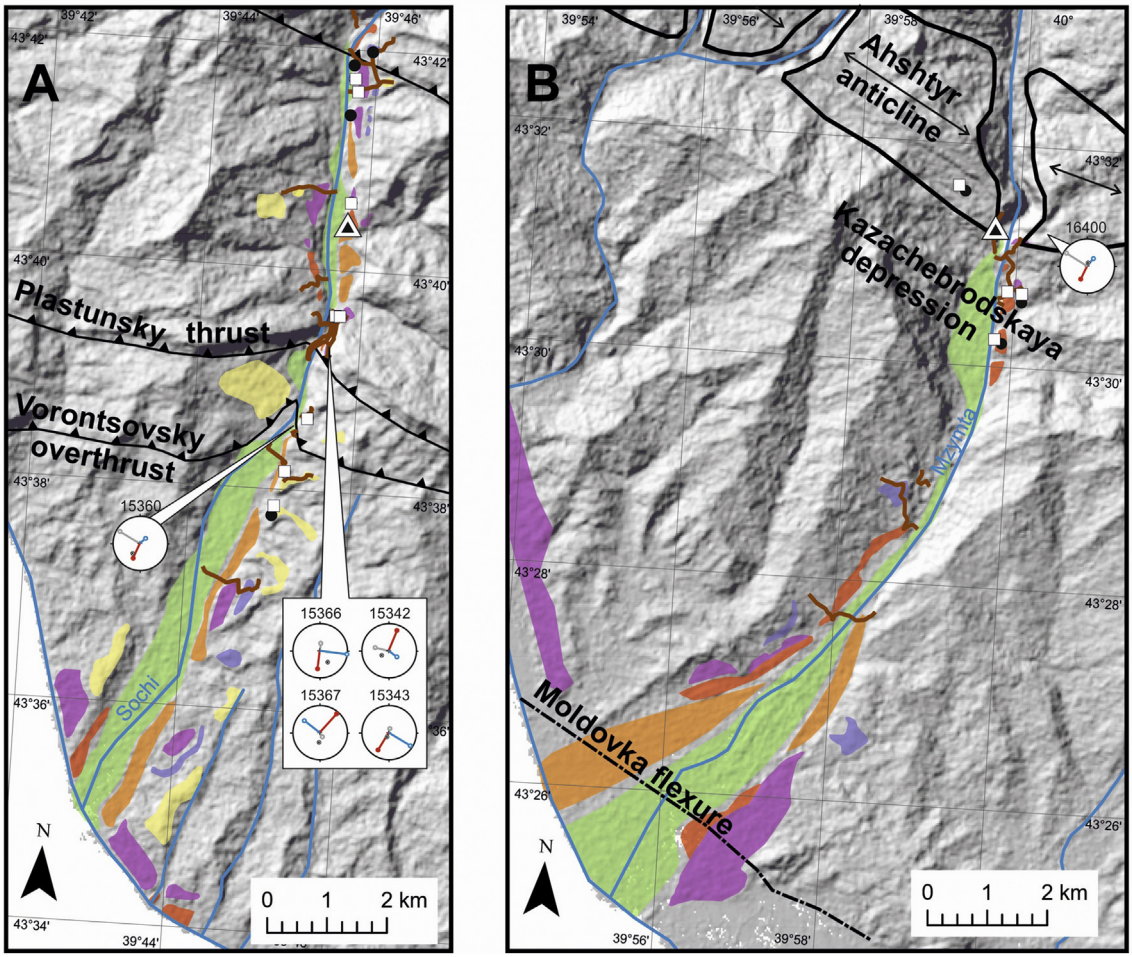

Fig. 3. Terraces of the Sochi (A) and Mzymta (B) rivers and the adjacent marine terraces on hillshaded ASTER GDEM. Floodplain is shown with green; Pavlovskaya (Sochi marine) terrace, orange; Popovskaya (Agoy marine), red; Pugachevskaya (Shakhe marine), magenta, Partizanskaya (Ashe marine), navy blue; other terraces, yellow. Triangles, archaeological sites; sampling sites: white boxes, faunistic, black circles, pollen; brown solid lines, levelling profiles. Stereoplots of local stress (lower hemisphere) are labelled with sampling indices; red axis, maximal principal stress; grey axis, intermediate; blue axis, minimal; 'x' mark, poles of bedding planes. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

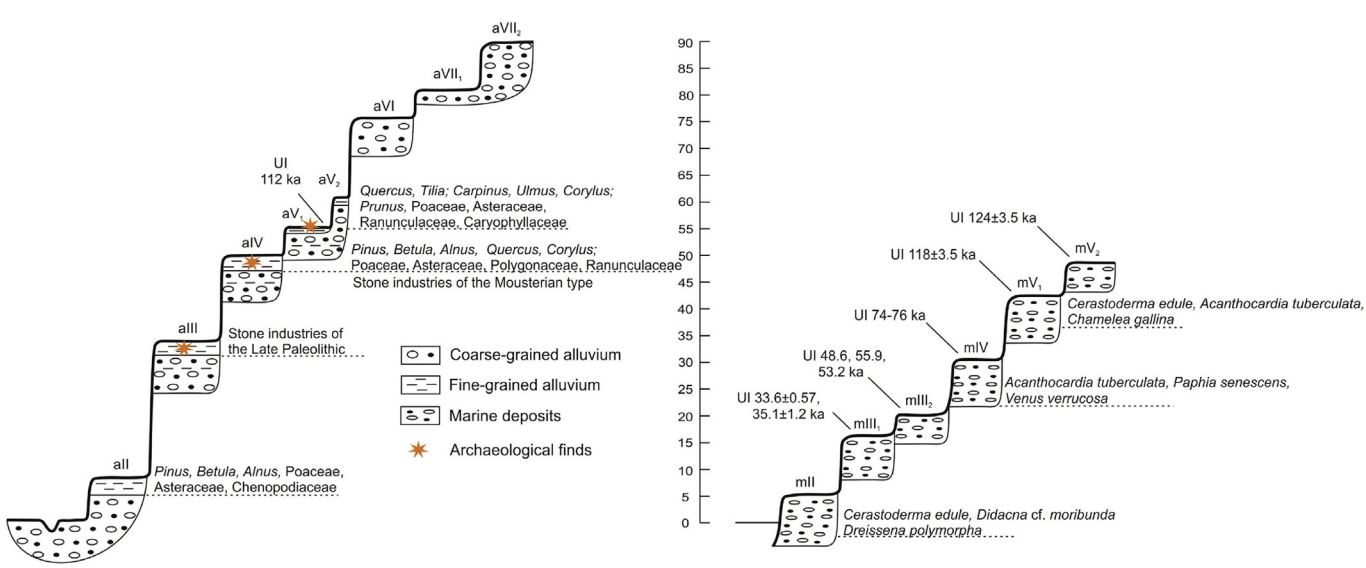

Fig. 4. Correlation of the river terraces and their marine analogues of the Sochi morphotectonic region.

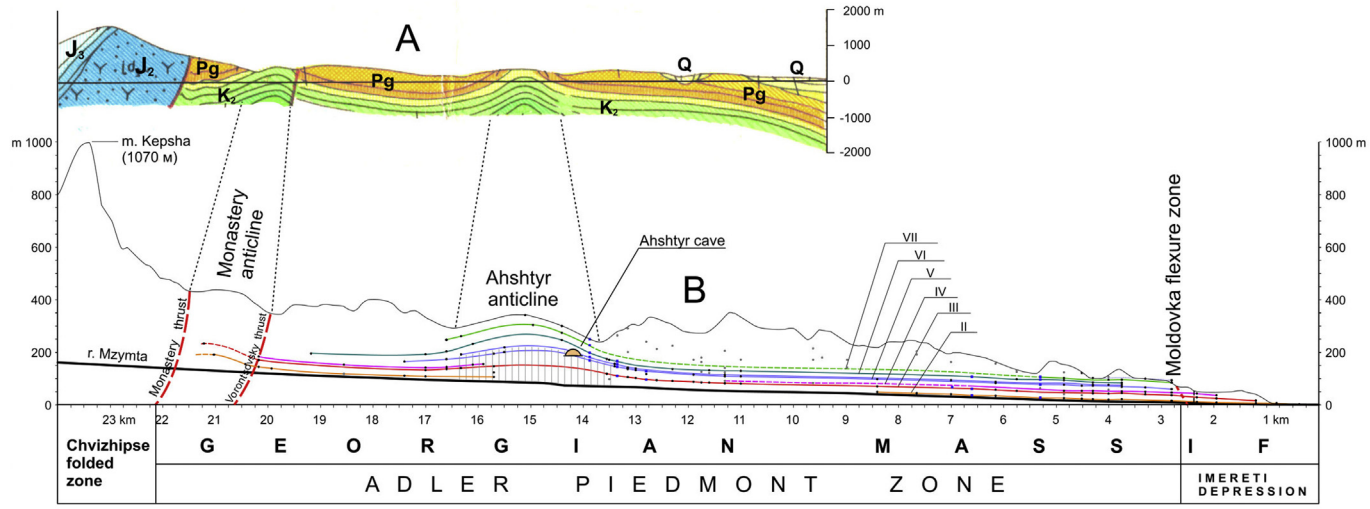

Fig. 5. A. Geological profile of the Adler morphotectonic subarea (line Krasnaya Polyana - Leselidze). Geological units are shown with indices. Simplified from State Geological Map of the USSR (State Geological Map…, 1964). Horizontal and vertical scales are equal. B. Geomorphologic profile of the Adler morphotectonic subarea along the Mzymta valley from the mouth to Kepsha mountain. Black line is a topographic profile, bold black line – modern river channel. River terraces are shown with colour lines and roman numbers (see table for details), dashed where inferred. Sites of levelling are shown with dark blue boxes, measurements by DEM are shown with black circles. Measured sites on older terraces are shown in grey. Dashed is the Upper Pleistocene - Holocene incision of the Mzymta River. Vertical scale is exaggerated. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

early Late Pleistocene Eemian interglacial (MIS 5e).

The age of the V terrace has been supported by archaeological finds. The Palaeolithic site named Ahshtyr Cave is situated above the Ahshtyr gorge (Figs. 3 and 4). The cave has two entrances at 97 m and 102 m above water level, the bottom of the cave rests on the lower subzone of Partizanskaya terrace. The bottom of the upper sublevel of ancient Ahshtyr canyon is situated 8–10 m above the cave. At the top of the sublevel within slope detritus well-rounded elongated river pebble is found.

Both erosional levels have been surveyed downstream to Ahshtyr homoclinal depression, where they appear on the surface of the two-levelled Partizanskaya terrace, having a normal undisturbed altitude of 52 m above water level.

Cave sediments of the Ahshtyr settlement were described in details and their age was determined earlier (Kulakov et al., 2007; Kulakov and Pospelova, 2012; Baryshnikov, 2012). The lower part of alluvium is represented by well-rounded river pebble, yielded a thermoluminescence date of 306 ± 61 ka (RTL-926) (Kulakov et al., 2007). However, the pebble found 30–50 m from the entrance is likely to be brought through sinkholes in cave roof from the surface of the upper sublevel of the Partizanskaya terrace described above. The uplift of the cave below the water level occurred during the Middle Pleistocene, 200–150 ka (Nesmeyanov, 1999). Archaeological finds of Mousterian type in the middle part of the cave sediments section, dated by the carbon layers from ancient firesites (RTL-927), provide data for the first *Homo neanderthalensis* settlement of 112 ka (Kulakov et al., 2007). These dates support the hypothesis that the cave uplifted above the level of the fluvial accumulation at the end of the Moscow glaciation (Riss-II, MIS 6).

Higher river terraces are also described in the region (Scheglov, 1986; Nesmeyanov, 1992; Nesmeyanov and Izmailov, 1995; Izmailov, 2007; State Geological map …, 1999; Ob'yasnitel'naya zapiska …, 2010), but within the investigated area they were found fragmentarily and without sedimentary cover. As a result it is difficult to date the terraces and use them for modern tectonic movement estimations.

4.2. Dating and correlation of fluvial and marine terraces

The II fluvial Pavlovskaya terrace in the lower reaches of the Mzymta and Sochi rivers correlates to the Sochi marine terrace (Fig. 3). Deposits of the Sochi terrace (mII) lie at altitudes of 4–6 m near Sochi city and are presented by pebblestone, shell rock and gravelly sand containing *Cerastoderma edule* (Linnaeus, 1758); *Didacna cf. moribunda* Andrussov, 1918; *Dreissena polymorpha* Pallas, 1771, with total thickness of 3–4 m (State Geological map …, 1999).

The two-level III fluvial terrace has been traced from the lower reaches of the Mzymta and Sochi rivers where it clearly corresponds to the Black Sea terraces: Early Agoy (U-Th-dating yielded 48.6; 55.9; 53.2 ka) ($mIII_2$), Late Agoy (U-Th-dating yielded 33.6 ± 0.57 and 35.1 ± 1.2 ka) ($mIII_1$) (State Geological map …, 1999) (Fig. 3).

The IV fluvial terrace correlates to the Shakhe marine terrace (mIV) (Fig. 3) at the Mzymta and Sochi mouths. The Shakhe terrace is located at altitudes of 30–31 m and is widespread in the Sochi morphotectonic area. It is composed by pebblestone, detrital sands with interbedded clays containing molluscs *Acanthocardia tuberculata* (Linnaeus, 1758), *Paphia senescens* (Cocconi, 1873), *Venus verrucosa* Linnaeus, 1758 and others. U-Th-date of 74–76 ka was obtained in the 20–35 m thick sections near the Sochi city (Scheglov, 1986).

The two-level V fluvial terrace correlates to the two-level Ashe terrace of the Black sea (mV) with altitudes of 43–48 m. Marine deposits of the mV terrace consist of bouldery-pebble deposits up to 2.5 m thick with sparse shells of Mediterranean type *Paphia senescens* (Cocconi, 1873), *Cerastoderma edule* (Linnaeus, 1758), *Chamelea gallina* (Linnaeus, 1758) etc. (State Geological map …, 1999). U-Th-dating of the lower Ashe terrace (mV_1) that corresponds to the lower sublevel of the V terrace yielded 118 ± 3.5 ka (State Geological map …, 1999). The age of marine sediments of the upper sublevel (mV_2) is 124 ± 3.5 ka (U-Th) (State Geological map …, 1999). The age of both sublevels corresponds to the Black sea Karangat transgression (an age analogue of the Tyrrhenian transgression of the Mediterranean Sea) and to the beginning of the Mikulinian (Eemian) interglacial period (MIS 5e), that is confirmed by pollen data from terrace alluvial sediments.

4.3. Deformations of the fluvial terraces

4.3.1. Adler morphotectonic subarea

The study of the Adler morphotectonic subarea reveals that the height of the Mzymta river terraces increases upstream. The height of

the terraces increases one relative to another as well. The increase is nearly proportional to their age. In particular, the height of the II terrace changes from 5 to 13 m above water level along its 18-km segment, i.e. the terrace rises by 8 m. The height of the III terrace increases similarly from 24 to 38 m, i.e. by 14 m (Fig. 5).

The rate of the incision can be estimated by the deformation magnitude of the V terrace, formed during the Karangat transgression, with the sea level similar to the recent one. This terrace has the relative height of 72 m in 10 km from the Mzymta mouth, which is 22 m higher than in the mouth of it. According to this, the rate of the Mzymta incision can be estimated as 0,18 mm per year, which proves the slight general uplift of the mountain system during the Late Pleistocene-Holocene.

There are three tectonic disturbances in the Mzymta river terraces. Younger terraces and floodplain excessively lose their height at the estuary. For instance, the II terrace coalesce with the low floodplain level, and the New Euxinian sedimentary sequences of the Upper Pleistocene are up to 42 m thick beneath the Holocene sediments (State Geological map …, 1999). Subtracting a maximum of pre-Holocene marine regression equaling 25 m (Scheglov, 1986; Yanko-Hombach et al., 2011) from 42 m of Late Pleistocene – Holocene sedimentary sequences, the subsidence of New Euxinian sediments by at least 17 m during the Holocene were obtained. This happened due to the subsidence of the Imereti depression separated from the homocline of the Adler morphotectonic area by Moldovka flexure (Nikiforov and Kozhurin, 2011) (Figs. 2, 3 and 5).

The next tectonic disturbance zone is located at the intersection of the Mzymta river channel and the Ahshtyr anticlinal ridge (Fig. 3). The river cuts the antecedent valley forming the gorge with nearly vertical walls up to several hundred meters high. Near the Ahshtyr and Kazachiy Brod villages (when moving from SW towards the structural slope of Ahshtyr ridge) the level of the III terrace increases from 28 to 46 m (Figs. 5 and 6). The terrace changes its structure within the valley: the fill terrace within the depression turns into the strath terrace near the ridge slope (the bedrock increases its height towards the ridge slope) (Fig. 6). This strath terrace is traceable along the Ahshtyr gorge and lays 70 m above water level (Figs. 5 and 6). The V terrace splits into two levels, which change from a fill terrace within the depression to a strath terrace within the gorge. The height of these two terrace levels within the gorge on fold axis increases up to 127 m and 140 m respectively (Fig. 6). The absence of well-stratified cover on the top of the terrace and finds of well-rounded elongated pebbles in slope detritus confirm that it is a strath terrace. The V terrace is the highest within the modern Ahshtyr canyon (Fig. 6). At the same time, slopes of the elder valley that lies above the modern canyon were measured at heights of 180–350 m above water level. There, the elder terrace sequence consists of two terraces with treads tilted towards the sea at heights of 185–125 m and 215-155 m above water level. The SW edge of lower terrace has the same height as compared to the VI terrace. The upper level corresponds to the VII terrace. The bottom of this elder valley corresponds to the V terrace described above (its upper sublevel). The morphology of this wide valley with smooth slopes serves as evidence of Ahshtyr ridge slow uplift and the absence of deep antecedent valley at the initial stage of structure formation.

U-Th-date from the lower part of the Ahshtyr cave subaerial sediments section (112 ka – RTL-297 (Kulakov et al., 2007)), supports the Early Mikulinian (Eemian, MIS 5e) age of the V terrace (Fig. 7), revealed by U-Th-dating of marine terraces (State Geological map …, 1999) and pollen spectra. At that time, the upper level with cave on it was just above the floodplain, whereas the lower level was the floodplain at the bottom of wide elder Mzymta valley.

In general, Ahshtyr anticline has been active during the late Quaternary, which is expressed in ridge formation across the Mzymta river channel. The rate of uplift was likely low and gentle slopes had time to develop within the antecedent zone of the valley at the initial stage. Later the acceleration of the ridge uplift led to the formation of the gorge with 180 m nearly vertical walls.

Active Monastery anticline further upstream of the Mzymta (Fig. 3) has been revealed. Due to the anticline formation the II terrace was uplifted by 40 m, the III terrace by 55 m. Geological section of the

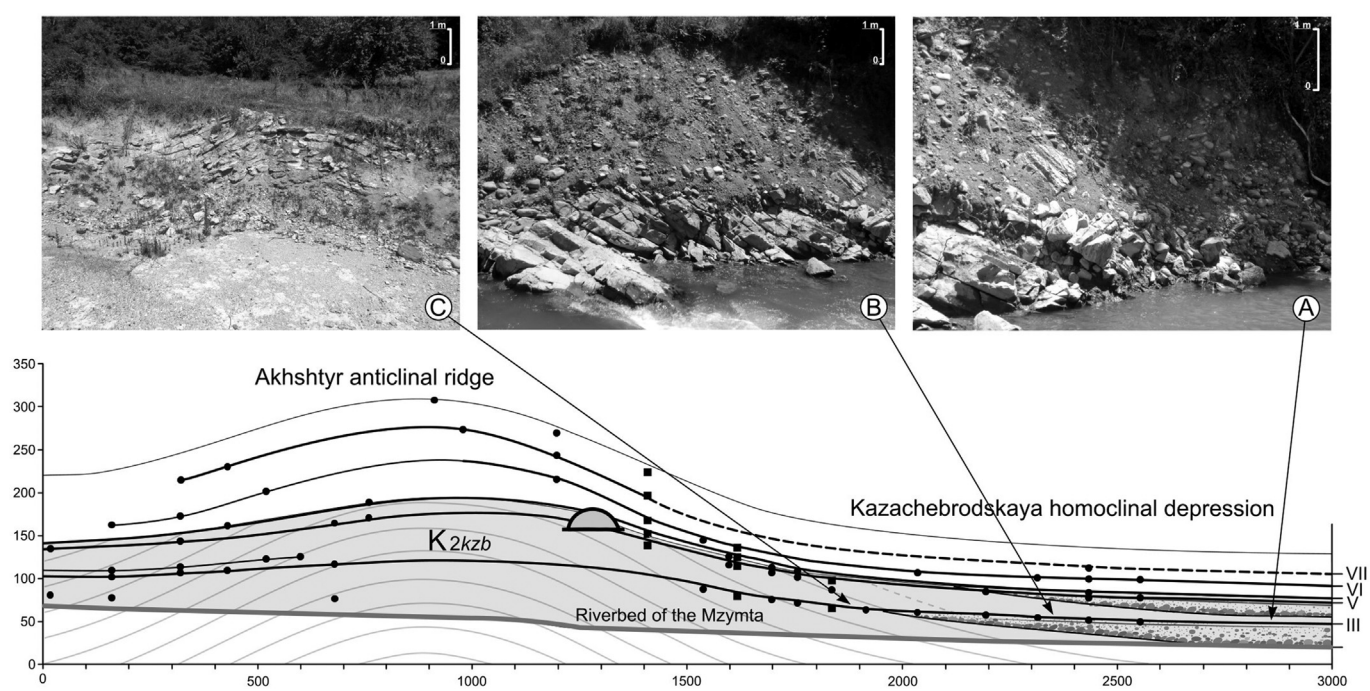

Fig. 6. Correlation of the terrace levels within tectonically disturbed (Ahshtyr canyon) and non-disturbed valley zones. Bold black line – modern river channel. River terraces are shown with black lines and roman numbers, dashed where inferred. Sites of levelling are shown with black boxes, measurements by DEM are shown with black circles. The volume of Late Pleistocene-Holocene incision is shown by light grey fill. Letters indicate: A - sector of the III terrace with fill structure; B - sector of the III terrace with socle structure; C - strath sector of the III terrace, K2kzb - Kazachebrodskaya formation of the Late Cretaceous (layered limestone, variegated limestone, marls). Photos by Y.I. Trikhunkov.

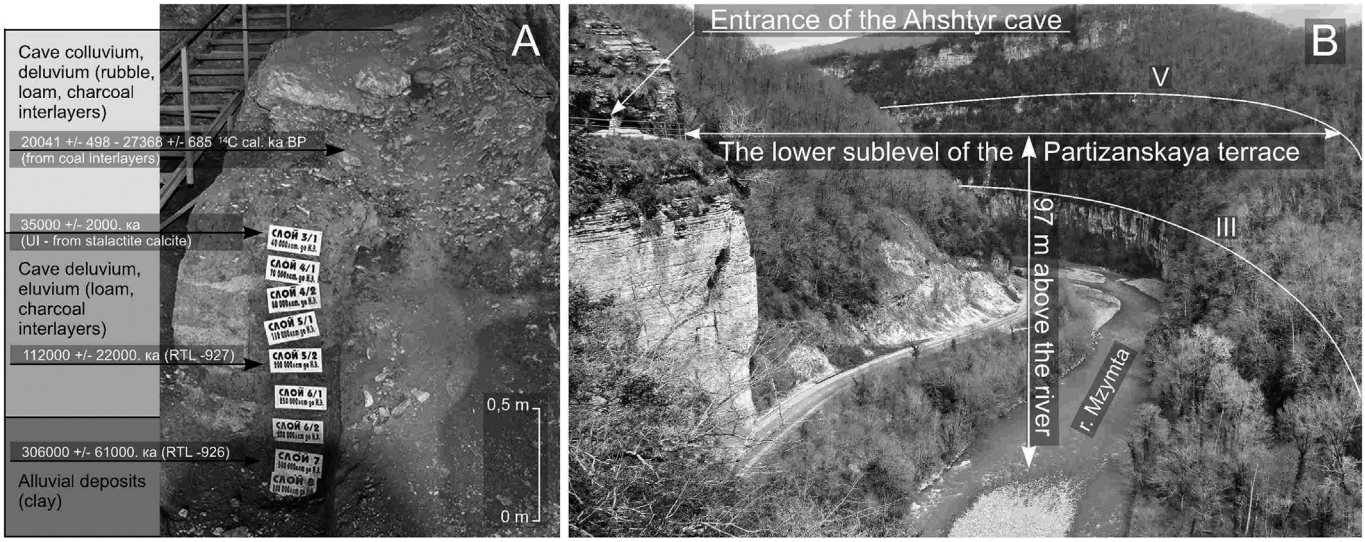

Fig. 7. The Ahshtyr cave on the ledge of the V terrace in the Ahshtyr canyon (B) and a section of cave deposits (A). Roman numerals indicate terraces. Photos by Y.I. Trikhunkov. UI – U-Th, RTL – thermoluminescence samples (Kulakov et al., 2007).

anticline is described within the roadway excavation of Krasnaya Polyana highway. S.A. Kulakov (personal communication) has found a cave with several Mesolithic implements 12 m above water in the anticline core similar to Ahshtyr site.

Within the Adler morphotectonic subarea there are several anticline and brachyanticline ridges that are analogous to the Ahshtyr ridge. They are of general Caucasian strike and dissected by antecedent gorges of NE-SW direction (Fig. 3). Among them there are the Akhun and Bytkha ridges, the morphology of which serves evidence for the young age of these folded structures. These structures are very similar to those described by Milanovsky as a classical example of the initial brachyanticline ridge within the Girdyman-Chai river delta in the South-eastern Caucasus (Milanovsky, 1968). They consist of the Upper Cretaceous carbonates and Paleogene terrigenous sediments, exposed along the fold axes. These structural, morphological and lithological data are similar to Ahshtyr, thus the whole subregion experiencев the initial folding of the sedimentary cover of the Georgian Massif caused by the involvement of the latter into folding of the Great Caucasus.

4.3.2. Plastunka morphotectonic subarea

Fold-thrust dislocations of the Vorontsovsky nappe (allochthon) predominate in the Plastunka subarea in the Sochi river basin (Figs. 3 and 8). The main tectonic landforms of the region, the Plastunka depression and the surrounding thrust ridges Alek, Navaginka and Mamaika have been studied. The Plastunka depression is located within the nappe and is complicated by thrust-related folds.

Four terraces with alluvial covers have been distinguished in the valley of the Sochi river within the Plastunka depression, as well as some higher terraces with alluvial cover which was not preserved. As for the Mzymta valley, the highest terraces have been surveyed but omitted in calculations of rates and magnitude of tectonic deformations. The age of the Sochi River terraces have been determined by river and marine terrace correlation, pollen dating and isotopic dates from published data (State Geological map …, 1999; Shchelinsky, 2007). The floodplain and the II to V terraces have been investigated.

Three levels of mainly fill floodplain up to 4 m height within the Plastunka depression presumably correspond to the Late Pleistocene-

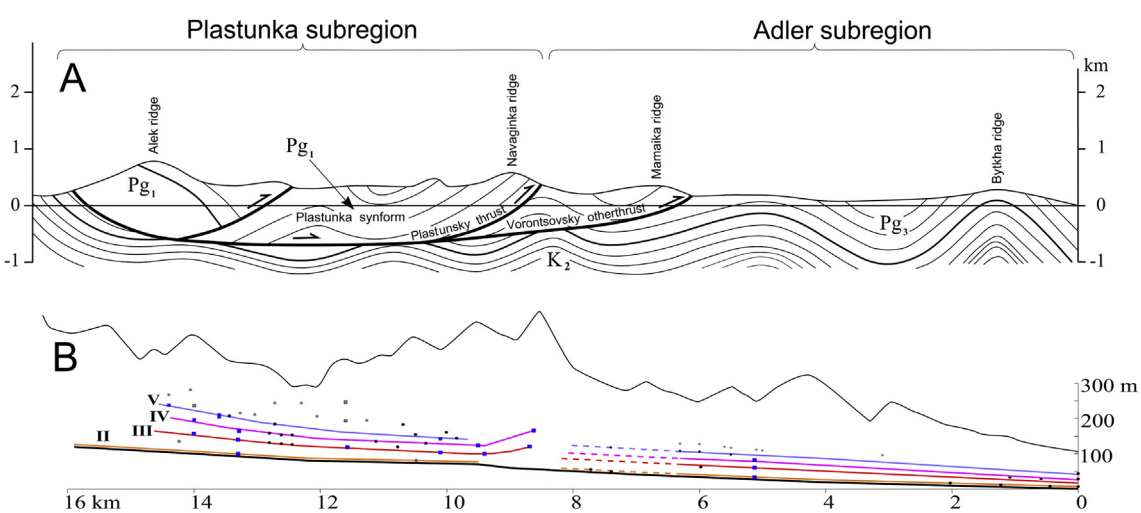

Fig. 8. A. Geological profile of the Sochi morphotectonic region along Sochi river valley (State Geological map …, 1999) with geological structures and tectonic landforms labelled. Geological units are shown with indices. Compiled using State Geological Map of the USSR (State Geological Map…, 1964). Horizontal and vertical scales are equal. B. Geomorphological profile of the Sochi morphotectonic region along Sochi river valley. Black line is a topographic profile, bold black line – modern river channel. River terraces are shown with colour lines and roman numbers (see table for details), dashed where inferred. Sites of levelling are shown with dark blue boxes, measurements by DEM are shown with black circles. Measured sites on older terraces are shown in grey. Vertical scale is exaggerated. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Holocene time. Terraces within the depression 10–16 km upstream from the Sochi mouth are relatively low: the II terrace has altitudes of 5–8 m (similar to coastal zone); III – 21–29 m; IV – 41–49 m. The V terrace is presented fragmentarily, therefore it is inappropriate for estimation because of its deformations. Thus, total uplift of the NWC described above is not expressed within the Plastunka depression.

At the north side of the depression the Sochi valley cuts through Alek thrust ridge. Fault zone here is represented by a 20-m thick system of thrusts with slickensides and fault breccia. However, there are no river terraces developed enough to study the active tectonics.

The floodplain becomes strath near the south side of the depression, bordered by Navaginka ridge, that is located on a hanging wall of the Plastunsky thrust (branch of the Vorontsovsky overthrust) (Fig. 8). The floodplain bed rises towards the antecedent gorge Plastunka Gate (crossing the Sochi river by Navaginka ridge) and inside of the gorge the floodplain becomes erosional (without any alluvial deposits) and gradually rises up to a height of 3–10 m (on the exit of the gorge). On the steep gorge slope, Popovskaya and Partizanskaya terraces have been traced. They are raised respectively up to 25 and 50 m higher than their undisturbed position within the Plastunka depression (Fig. 8). Relative altitude of the V terrace above the III terrace which increases here indicates active uplifting of the ridge. One branch of the Plastunsky thrust with the width of 50–60 m has been described in the Palaeogene deposits at the gorge wall directly above the surface of the V terrace. It consists of the thrust system deforming the Paleogene formations, brecciated and altered by contact metamorphism (multiple slickensides, carbonate and ferruginous mineralization). Thrust plane crossing the Sochi valley deforms the river channel and forms a scarp about 3 m high, which indicates the recent activity of the fault.

Thus Plastunka morphotectonic subarea, the sedimentary cover of which is located within Vorontsovsky nappe allochthon, has more complicated pattern of morphotectonic development as compared to that of the Adler subarea which sedimentary cover is preserved. Folded deformation with subsidence of central part of Plastunka synform compensates the overall uplift of the region. The southern border of the depression above the Plastunsky thrust is rising, it is expressed in the modern topography of the subarea with the Plastunsky thrust forming a steep southern slope of the Navaginka Ridge (Figs. 2 and 3). In general, the structure of the Plastunka subarea, representing the final stage of destruction of folded structures with overturned folds and overthrusts, is more mature than the structure of the Adler subarea.

4.4. Tectonophysical data

The activity of the Vorontsovsky overthrust and Plastunsky thrust were confirmed by field study of slickensides. Brittle structural data have been collected from the Upper Cretaceous to Oligocene rocks. These structures have a possible period of formation during the whole Cenozoic period including Quaternary time and reflect the state of stress of this stage of deformation in the region. Determination of the precise time of formation of mineral fibres or fault gouge was not possible. The paleostress reconstruction has been conducted using the method of cataclastic analysis of discontinuous displacements (Rebetsky et al., 2012). It has revealed all the components of stress tensors and quasi-plastic (faulting) strain increments, together with the estimation of strength parameters of brittle rock massifs, corresponding to the most representative dimension of faults used for the reconstruction. The program STRESSgeol, created in the laboratory of Tectonophysics of IPE RAS (http://old.ifz.ru/tecton_stress/index.html (in russian)), was used to compute the local stress tensors.

The observed fault structures correspond to the single stress regime. Reverse and thrust faults have WNW-ESE strike with NNE fault plane dip. Subvertical tension structures have predominantly N-S strike. There are many subhorizontal tension structures as well, which are the evidence of nappe-and-thrust faulting (minimum compression or deviator tension axis is oriented subvertically). Sinistral strike-slip faults with northeastern strike (from NNE to ENE) are the most widespread on the territory. Dextral strike-slip faults with meridional strike occur rarely. The majority of small faults is related to NNE compression with formation of thrust (nappe) and strike-slip structures. The inversion of more than 100 slickensides data, collected at 11 sites in the Sochi region, provided data for reconstruction of 11 local stress tensors. The tension gashes are taken into additional account for definition of the minimum principal stress direction. Nine stress states characterize a strike-slip and compressional regime with NNE-SSW directed maximal principal stress axis. The computed local stress state in the Sochi region is typical for both the main stage of folding (Saintot and Angelier, 2002; Rastsvetaev et al., 2010; Marinin and Saintot, 2012) and the recent stage (Angelier et al., 1994).

5. Discussion

The available data allow to study the late Quaternary and recent tectonics, estimate magnitudes and rates of movements. The height of the terraces above water level and above each other was calculated to estimate the rate of the uplift of the mountain system. The procedure is valid only if the base level is known. It was the same as recent during the formation of the Early Karangat marine terrace (MIS 5e) with the age of 124 ± 3.5 ka (U-Th) as well as the V river terrace formation base level was the same as today (Scheglov, 1986; Izmailov, 2007). The rate of the Mzymta incision expressed in the V terrace heights can be estimated as 0.18 mm per year. However, this rate cannot be considered as direct evidence for the rate of the tectonic uplift as it also depends on the lithology, climate and some other factors.

The obtained data serves as evidence for active subsidence of the Imereti depression. The age of the first terrace sediments buried by 42 m in the Mzymta mouth equals 10.488 ± 2.53 ^{14}C cal. ka BP (State Geological map …, 1999). The Black sea level at that time was about 20 m below the contemporary level (Yanko-Hombach et al., 2011), thus the magnitude of the Holocene subsidence comprises 22 m with a rate of 1.8 mm per year.

The uplift rate of the Ahshtyr ridge derived from deformations of the III terrace is 1 mm per year, 0.7 mm per year for the V terrace, 0.27 mm per year for VI terrace. Thus, the uplift rate increased from the Middle Pleistocene to the Holocene.

The formation of the young Ahshtyr gorge with the Ahshtyr cave on top of it is the result of the uplift acceleration (Figs. 5 and 6). The settlements of this type were usually disposed by water and were located at the floodplain or the first terrace level (Kulakov et al., 2007; Shchelinsky, 2007). It proves the fact that there was no Ahshtyr canyon during the cave inhabitance period (Fig. 5). The cave was first inhabited 112 ka ago. The archaeological finds of Mousterian type, appearing in the middle part of the cave sediments section, dated by thermoluminescence method, proved this age (RTL-927) (Kulakov and Pospelova, 2012). This probably occurred due to the migration of Neanderthal man from the seashore towards the continent during the warmer Mikulinian (Eemian) interglacial period.

The Ahshtyr site was actively used until the Middle Palaeolithic. The last active usage period happened during cold dry climate, it is confirmed by two dates: the first one corresponds to Laschamp polarity event (Kulakov and Pospelova, 2012) 40.2 ± 2.0 ka (Markova et al., 2008), the second one is 35 ± 2 ka by U-Th dating of calcite (Kulakov and Pospelova, 2012) (Fig. 7). Later, within the period of 20–27 ka (Kulakov and Pospelova, 2012) the cave was used episodically by the Late Palaeolithic man. It can be explained by the acceleration of the uplift of the ridge and the subsequent retreat of the cave from the water source (lack of water in the karst cave).

The Plastunka morphotectonic subarea is characterized by different tectonic patterns and rates of active tectonic deformations. As it is stated above, the overall uplift is not observed here, which might be caused by the subsidence of the central part of the Plastunka synform, whereas fault tectonics is actively expressed on the periphery of it.

The calculations of the Navaginka ridge uplift (Figs. 2, 3 and 8) can be estimated on the assumption of the age of three geomorphic levels. The III terrace with the age estimated within 55.9 (UI)-33.6 ± 0.57 ka (UI) (State Geological map …, 1999), is deformed at the Plastunsky thrust zone by 25 m. The elder IV terrace (74–76 ka (UI), (State Geological map …, 1999) is uplifted by 50 m. High floodplain, which is younger than the II terrace, and probably corresponds with the time of the Upper New Euxinian sediments formation (10.53 ± 1.90 ka (RU) (State Geological map …, 1999), is deformed at the same thrust by 6 m. These data make it possible to estimate the Late Pleistocene rates of the Navaginka ridge uplift as 0.5 mm per year, 0.56 mm per year and 0.66 mm per year taking into account the deformation of the high floodplain, the III and IV terraces correspondingly. As it is mentioned above, the Sochi River channel has a 3 m high scarp at the intersection with the Plastunsky thrust. Extrapolation of the data on the deformation rate of the Late Pleistocene terraces allows to accept the minimum rate of deformation by the Plastunsky thrust as 0.5 mm per year during the Holocene. Based on these rates and on their variations in time it can be supposed that the Navaginka ridge had undergone relatively equable tectonic uplift during the Middle-Late Pleistocene – Holocene.

The local active tectonic structures of the NWC like the Ahshtyr or Navaginka ridges are entirely located in the extra-glacial region. This is confirmed by the absence of glacial deposits in sedimentary sections of river terraces of the Sochi area. In this regard, the influence of the glacial isostatic uplift is excluded, thus the acceleration of the uplift of the described structures has a tectonic origin.

Thus, active folds and faults, directly expressed in the topography of the region, are the characteristic features of the Sochi morphotectonic area. The pattern and rates of the described deformations differ in two subareas of the Sochi area. Active development of young (Quaternary) folded structures is specific for the Adler subarea, and is characterized by activation of the uplift during the Middle Pleistocene and acceleration during the Late Pleistocene-Holocene. All of them have become the result of the primary folded dislocations of sedimentary cover of the Georgian Massif, caused by submerging of the latter in the structure of the forming folded Great Caucasus mountain system, serving as examples of the initial stage of the folded structures formation.

Thus, the terraces on the surface of the Plastunka synform (Vorontsovsky overthrust) do not show any signs of uplift and are not disturbed by the differentiated folded tectonics in spite of more ancient age of structures in comparison with the Adler subarea. Deformations of the Sochi river terraces in the antecedent Plastunka Gate gorge are caused by the Plastunsky thrust development on the periphery of the synform (Fig. 6). The deforming rate of 0.5–0.6 mm per year have been constant during Late Pleistocene-Holocene.

It should be mentioned that active folded structures have been also described in the axial zone of the mountain system in the Goytkh area and its north-western periphery in the Taman area (Fig. 1) (Trifonov, 1999; Trikhunkov, 2016). The published data shows that the active formation of inherited fault-folded as well as young folded structures has been in progress in the NWC. They are developing in conditions of lateral compression with horizontal shortening in SSW-NNE direction, which can be caused by collision of the Georgian massif and the Scythian Plate. This conclusion agrees with the obtained data on tectonophysics.

6. Conclusions

1. In the Northwestern Caucasus, active development of both fault-folded and young folded structures continues. These structures are developed under conditions of lateral compression with a horizontal shortening in the NNE-SSW direction which can be explained by collisional interaction of the Georgian Massif and the Scythian Plate.
2. Recent deformation of the Northwestern Caucasus inherits the direction and kinematics of the Alpine folded structure with general NW extension. The stress regime typical for Alpine stage is expressed in recent folding and faulting.
3. Deformations of the river terraces of the Sochi morphotectonic area indicate the Mzymta incision rate as 0.18 mm per year. This can be explained by an arched uplift of the mountain system of the Northwestern Caucasus, though the data do not allow to estimate the exact rate of the uplift.
4. A series of folded and faulted tectonic landforms complicating the general arched uplift of the mountain system are actively developing under the conditions of lateral compression. The process is revealed by river terraces deformation. The rate of the young Imereti depression subsidence is up to 1.8 mm per year; the Middle Pleistocene Ahshtyr anticlinal ridge is uplifting at an average rate of 1 mm per year, that demonstrates an increase during the Late Pleistocene-Holocene time; the Navaginsky thrust ridge experiences a stable uplift at a rate of 0.5–0.6 mm per year during the last 120 ka.
5. The Plastunka and Adler subareas of the Sochi morphotectonic area are at different stages of folded structures evolution. It is found out that isolated anticlinal and brachyanticlinal ridges are specific for Adler subarea. They demonstrate the initial stage of folds development as the result of the initial dislocations of the sedimentary cover of the Georgian Massif. It is caused by the involvement of the latter into developing folded structure of the Greater Caucasus. The structure of the Plastunka subarea is more mature. Here, the final stage of destruction of folded structures, caused by the development of overturned folds, large thrusts and overthrusts, is presented.

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