RUSSIAN JOURNAL OF EARTH SCIENCES, VOL. 4, NO. 3, PAGES 233–241, JUNE 2002

Seismic and tectonic activity of faults on the south slope of the NW Caucasus

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Abstract. Paleoseismologic studies of recent years on the southern slope of the Northwest Caucasus show major earthquakes of up to M 7.0 to have occurred in the past in the number of geologically active fault zones. Recurrence interval of such seismic events is on the order of 2000 years. The rate of geologic displacement (creep) on the faults over the past 100 years is assessed at 1.5 to 2.0 mm/yr.

Introduction

In recent years, geologic-geomorphologic studies have been conducted in the Northwest Caucasus, aimed at revealing traces of unknown large past earthquakes in active fault zones. The studies were focused on paleoseismologic issues and involved trenching and test-pitting across those landforms that could be classed as seismic ruptures caused by past earthquakes. Earlier, similar studies were conducted on the Greater Caucasus [*Paleoseismogeology...,* 1979] and on the Lesser Caucasus [*Rogozhin and Filip,* 1991], and they demonstrated the applicability of such techniques to the Caucasus region as a whole.

Geologic-Geomorphologic Study of Fault Zones

Field studies conducted in 2000 and 2001 on the south slope of the Northwest Caucasus, in the Vulan–Dzhubga interfluve, identified a number of geologically and seismically active faults. As regards the place of these faults in the evolution of the Greater Caucasus orogen, they fall distinctly into two groups—more ancient, synfolding, and younger, neotectonic. Numerous landslides of various ages are associated with the neotectonic faults. Some young ruptures are traceable on the surface as well-marked scarps. The study of these previously recognized tectonic lineaments [*Nesmeyanov,* 1992] by means of hiking traverses, trenches, and test pits shows all these hypothetical faults, both within tectonic zones on the northern slope of the Great Caucasus meganticlinorium and in the Semigorsky and Anapa–Agoisky tectonic zones of the southern slope (Figure 1), to be expressed as narrow linear belts of jointing or as bedrock ruptures. Overall, tectonic displacements, slickensides, and planar weathering zones extending deep into the subsurface are observed in association with the ruptures and faults.

Data on fold and fault structures in the Northwest Caucasus were collected and systematized in the form of three structural-geologic transects across the strike of the orogen. The transects were drawn through all the principal zones of the meganticlinorium, (i) along the Dzhubga–Goryachy Klyuch motor road, (ii) along the line Bezeps–Inal Cove, and (iii) along the Novorossiisk–Rostov motor road. The cross sections were constructed at 1:25,000 scale. During fieldwork, shapes of folds of various orders, lithologies, and all the major and numerous minor faults were recorded on the cross sections.

In order to elucidate the deep structure, features observed in the nearsurface portion of the sections were continued downward to basement surface. This exercise was performed with due account for thickness of geologic horizons, as assessed from stratigraphic columnar sections for each tectonic zone, and for the style of major- and medium-size folds (dip of limbs and axial surfaces, angle between limbs, etc.).

Paper number TJE02095.
ISSN: 1681–1208 (online)

The online version of this paper was published 16 May 2002.
URL: http://rjes.wdcb.ru/v04/tje02095/tje02095.htm

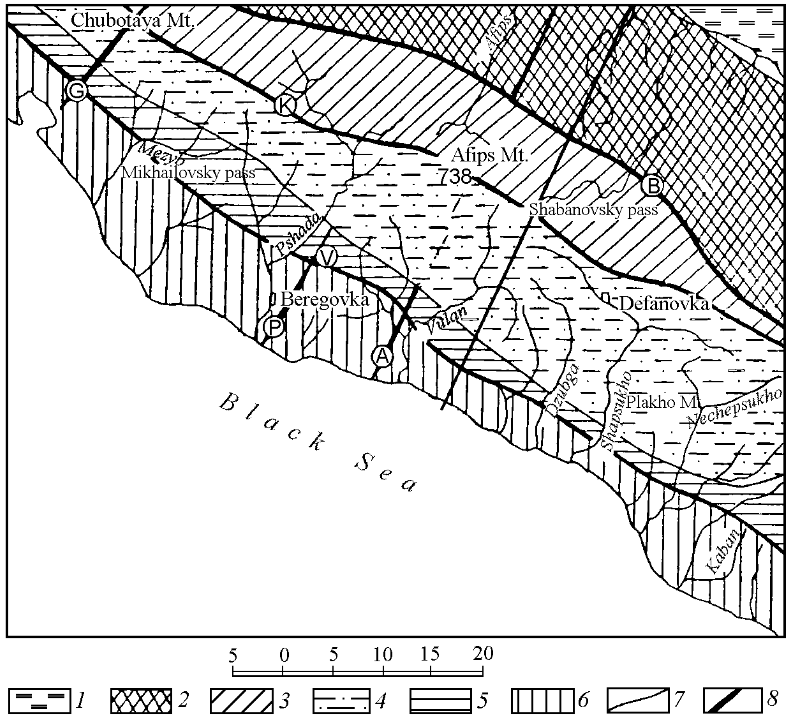

Figure 1. Tectonic scheme for the study area.
1–6 – tectonic zones: 1 – Abino–Gunaisky, 2 – Goitkhsky, 3 – Papaisky, 4 – Tkhabsky, 5 – Semigorsky, 6 – Anapa–Agoisky; 7 – boundaries of lengthwise tectonic zones; 8 – transverse faults: G – Gelendzhik, P – Pshadinsky, A – Afipsky. Lengthwise transpressional strike slip faults: B – Bezeps, K – Kotsekhursky, V – Vulan. Straight line I indicates location of cross section (Figure 2).

Data on basement topography were obtained from a magnetotelluric/earthquake converted-wave profile constructed by experts from "Kavkazgeolsyemka" (Caucasus Geologic Survey) and "GEON" Center [*Shempelev et al.,* 2001] and from other published data. Extrapolation of geologic data into the subsurface yields a somewhat arbitrary image of the Northwest Caucasus structure along the line Bezeps–Inal Cove, visible on the geologic-geophysical section to a depth of ca. 10 km (Figure 2).

Tectonic lineaments differ in terms of dominant strikes in different lithotectonic zones of the northern and southern slope. In the more northerly Semigorsky zone (Figures 1, 3), encompassing part of the south slope, and in tectonic zones composing the axial part and northern slope of the Main Caucasus Range (Goitkhsky, Papaisky, and Tkhabsky), the lineaments can be attributed chiefly to the two orthogonal structural directions, Caucasian (WNW or EW) and "anti-Caucasian" (roughly N–S). In the Anapa–Agoisky flysch zone of the south slope, principal faults belong to the diagonal NE and NW structural trends.

In the former instance (in northern zones), the ruptures are mainly reverse faults and overthrusts (where their orientation is Caucasian) or dextral transtensional strike slips (with anti-Caucasian strike). In the latter instance (in the southernmost zone), the faults are dominantly represented by fractures accompanied by deep reworking of wall rocks without visible offset, ancient or young. For some faults, ancient displacements have been detected. These are mainly reverse faults and transpressional strike slips. In certain cases, evidence of young, neotectonic displacements is available as well, NW-trending structures being dextral strike slips or transpressional strike slips and NE-trending ones, sinistral strike slips and transpressional strike slips (Figure 3).

The most active faults on the south slope of the Main Caucasus Range appear to be Kuznetsovsky, Malobzhidsky, Beregovoi (Coastal), Drovyanoi, and Verkhnekhazarovsky [*Rogozhin et al.,* 2001]. In specially excavated trenches, these fault zones display recent ruptures with a throw between 0.5 and 1.5 m, the displacements (on both reverse and strike slip faults) having been, in all likelihood, of impulse, seismogenic character [*Rogozhin and Ovsyuchenko,* 2001]. The faults cut not only bed rocks, but Quaternary strata as well, as, in the Verkhnekhazarovsky fault zone, even paleosoil with a cultural layer (Figure 4).

Evidence for Ancient Seismicity on Faults

Seismic character for recent displacements on faults is evidenced by the presence of well-marked debris wedges in downfaulted blocks (Figure 5). While studying nearsurface structure of these faults in trenches, we managed to constrain the age of recent seismogenic displacements on the Malobzhidsky and Verkhnekhazarovsky (Figure 4) fault

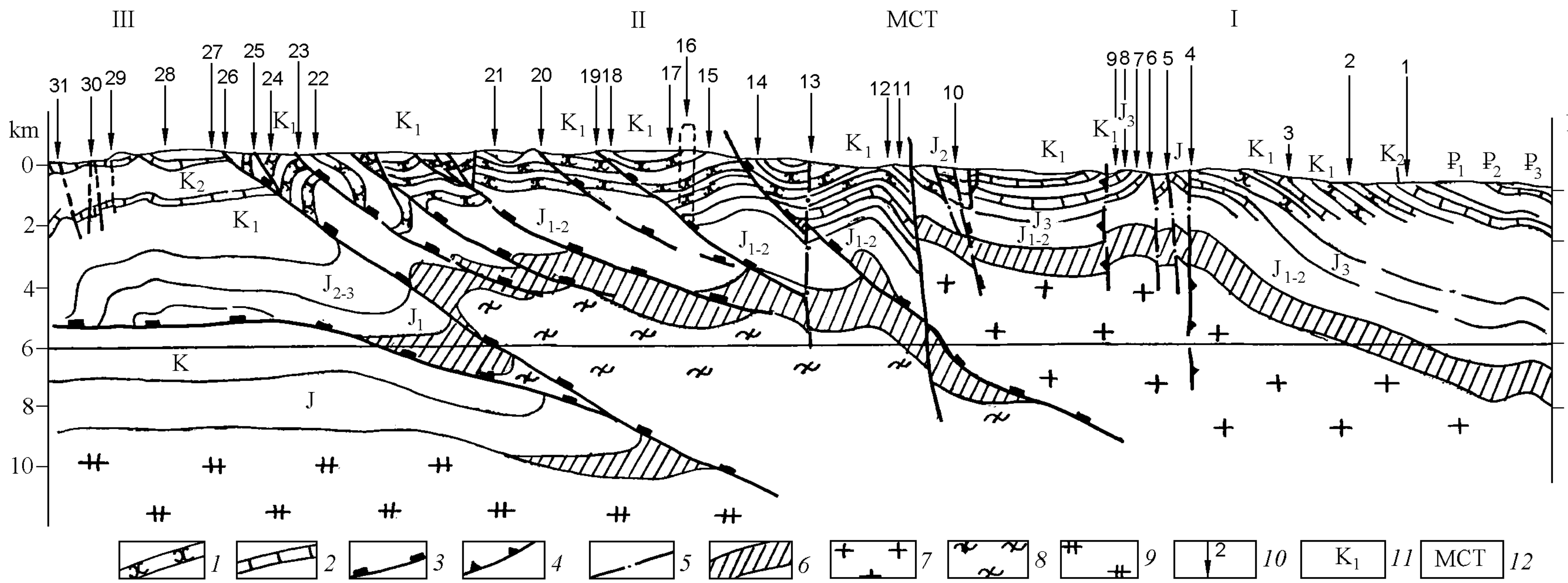

Figure 2. Balanced geologic–geophysical section through the upper crust of the Northwest Caucasus along the line Bezeps–Inal Cove (constructed by N. I. Ovsyuchenko, E. A. Rogozhin, and E. A. Ushanova using data from *Shempelev et al.* [2001]).
1 – Mesozoic terrigenous sequences; 2 – Mesozoic carbonate sequences; 3–5 – faults: 3 – reverse fault and thrust, 4 – transtensional strike slip fault, 5 – other; 6 – transitional (Upper Paleozoic) complex between cover and basement; 7–9 – pre-Mesozoic basement of folded system: 7 – North Caucasus marginal massif, 8 – plastic, of the Dizsky type, 9 – Transcaucasian (Dzirulsky) type; 10 – location of active neotectonic faults (after [*Nesmeyanov,* 1992]) and their tag number; 11 – age abbreviation; 12 – surface expression of the Main Caucasus thrust.
Numerals denote neotectonic faults: 1 – Psekabsky reverse fault, 2 – Leshchenkovsky reverse fault, 3 – North Shizsky normal fault, 4 – Gersevan thrust, 5 – Tkhamakhinsky reverse fault, 6 – Bezepchuksky normal fault, 7 – South Bezepchuksky low-angle normal fault, 8 – South Kobylyansky reverse fault, 9 – Shaumyan reverse fault, 10 – Shabanovsky normal fault, 11 – Burlachenkovsky normal fault, 12 – Pikhlerovsky normal fault, 13 – Severoperevalny normal fault, 14 – North Sinyavinsky normal fault, 15 – Sinyavinsky normal fault, 16 – Transverse Belokamensky transtensional strike slip zone (a, western branch; b, eastern branch), 17 – Belokamensky normal fault, 18 – Neberdzhaevsky normal fault, 19 – Shkalovsky normal fault (a, northern branch; b, central branch; c, southern branch), 20 – South Shkalovsky normal fault, 21 – Polkovnichy normal fault (a, northern; b, central; c, southern), 22 – North Savitsky normal fault, 23 – South Savitsky normal fault (a, northern branch; b, southern branch), 24 – West Savitsky normal fault, 25 – East Bzhidsky normal fault, 26 – Kuznetsovsky reverse fault, 27 – Malobzhidsky reverse fault, 28 – Verkhnekhazarovsky normal fault, 29 – Beregovoi normal fault, 30 – Drovyanoi transpressional strike slip fault,

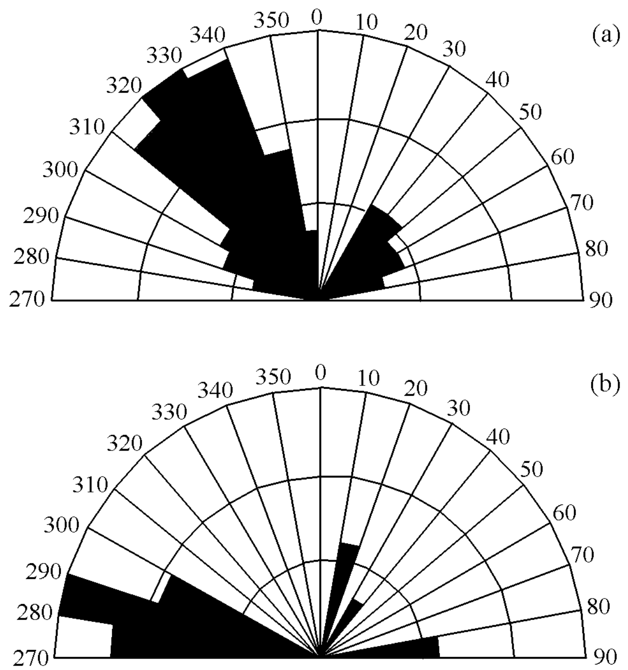

Figure 3. Rose diagrams showing fault orientations in the Northwest Caucasus: (a) for the Anapa–Agoisky lithotectonic zone and (b) for the Goitkhsky and Semigorsky tectonic zones (composed by E. A. Rogozhin and S. L. Yunga).

zones. Faulted paleosoils have radiocarbon (^{14}C) ages of 990±100 yr (IGAN-2126) for the former zone and 520±80 yr (IGAN-2118) for the latter. These pulse displacements can be correlated to large earthquakes known in the Crimea–Lower Kuban region, which occurred in the year 1341±1 and on September 16, 1799, respectively. Both seismic events had magnitude of at least M 6 and intensity ratings of 7 to 9 [*A New Catalog...*, 1977].

The case of modern displacements being documented in a NW-trending fault system is explained by the fact that a large extensional structure in the southwestern, steep part of a planated bench is associated with one such fault zone, referred to as Beregovoi. These displacements occur in the upper part of a landslide, incepted but not triggered, on the southwest slope of this small plateau. A trench dug across a large scarp in the plateau's edge (Figures 6, 7) exposes five major normal faults that strike NW and affect not only bedrock but eluvium, talus, and ancient soil horizons as well. The faults are 4 to 15 m apart and jointly make a complex small graben some 30 m in width, where dramatic changes are found to occur in the modern soil profile and in several fossil soil horizons.

The largest faults bound the graben on the northeast and southwest. They are accompanied by wedges that reach 4–5 m deep and are filled in with rock debris and soil material (Figure 6). Apparently, displacements on these faults are extremely young (in all likelihood, a few hundred to a few thousand years in age), are of pulse character, and have been repeatedly reactivated. One can discern four pulses of activity, expressed in the formation of debris wedges and horizons and talus aprons and in three phases of graben quiescence, evidenced by abnormally thick paleosoil horizons.

Besides the largest faults, the body of the "stabilized" landslide and its detachment zone are affected by numerous secondary faults, fractures, and jointing zones connected with repeated displacements of the landslide body. A number of such displacements are accompanied by zones of wall-rock reworking—mylonitization, limonitization, and carbonates crushed to powder. Some of the faults are devoid of such alterations.

Virtually all the faults, with rare exceptions, are extensional structures. Total extension, in as far as it can be assessed from the system of excavations in the landslide body, is likely to exceed 5 or 6 m.

Importantly, the young graben-like extensional structure is confined to the southwestern limb of an ancient NW-trending fault zone. The fault is expressed in two high-angle, SW-dipping, 30- to 40-cm-wide zones of jointing, brecciation, and limonitization. In the subsoil layer, these zones are continued upward by a thick eluvium pocket. These faults are situated in the central part of the trench (Figure 6). A scarp over 4 m in height, crossed by this trench (Figure 7), stretches for 550 m in a northwesterly direction. Further NW, the fault runs along a narrow cleft. To the southeast, the scarp ends 50–80 m short of the trench. Therefore, the length of the well-marked scarp is some 600 m. As one moves downslope, as many as three gentle benches with steeper slopes in-between are observed, which is characteristic of landslide topography.

Quaternary strata within the small graben and in the upper part of the steep slope are abnormally thick (3–5 m), and are distinguished by an appreciable variety of facies and by the presence of several thick horizons of buried paleosol, whereas normally, eluvial and talus deposits are no thicker than 1 m in this area. The modern soil layer in the study region is also thin, 20–30 cm, paleosoils being encountered only in active fault zones. It is worth noting that in the vicinity of the small graben and step-like steep slope, the forest is stable. Tree trunks are almost vertical, and there is no evidence of "drunk forest." The age of the oldest trees on this slope, which is of likely landslide character, is 230–260 yr (based on year rings). It thus can be ascertained that active movements along the scarp or on the slope have not resumed at least during that time. Radiocarbon datings on horizons of paleosoils and bones, collected from the walls of the trench crossing the graben, may be helpful in determining active displacement periods and stable development phases. The origin of this extensional near-fault structure can be tentatively attributed to strong surface shocks during large past earthquakes. To use the classification of the Irkutsk seismogeologic school, such seismic ruptures are termed gravitational-seismotectonic dislocations [*Paleoseismogeology...*, 1979].

Therefore, in the Beregovoi fault zone, the small seismogenic graben accompanying this NW-trending rupture is manifest in bed rocks and in Quaternary deposits. Here, the age of the modern soil is determined as 130±40 yr (IGAN-2418). A buried paleosoil horizon in the most sagged part of the near-fault graben yielded, from a depth of ca. 1.2 m, human bones, whose age was determined as 2980±90 yr (GIN-

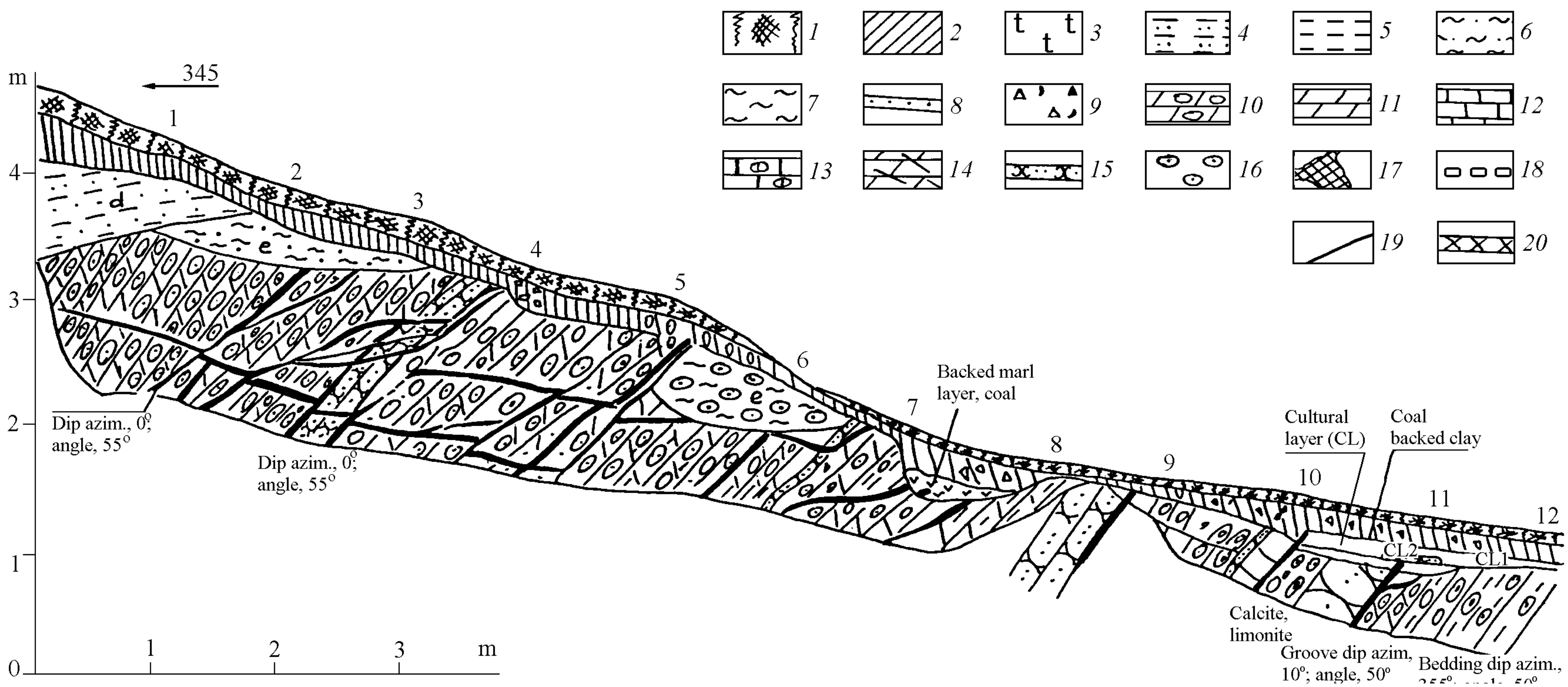

Figure 4. Sketch drawing of northeastern wall of a trench excavated across the active Verkhnekhazarovsky fault (composed by E. A. Rogozhin and E. A. Ushanova). Bold black lines depict individual reverse faults and thrusts.
Symbols to Figures 4–6 and 8: 1 – modern soil; 2 – various horizons of buried paleosoil; 3 – “technogenic” layer; 4–9 – Quaternary deposits: 4 – talus sandy loam, 5 – talus loam, 6 – eluvial loam, 7 – eluvial clay, 8 – sand intercalation, 9 – debris horizon; 10–15 – Upper Cretaceous bed rocks: 10 – weak shelly marl, 11 – strong layered marl, 12 – strong layered limestone, 13 – detrital limestone, 14 – jointed limestone and marl, 15 – strong sandstone; 16 – weathered, very weak shelly carbonate rocks or their roundish fragments; 17 – zones of mylonitization and other near-fault alterations; 18 – fragments of layers or boudinaged layers; 19 – individual fractures and minor faults; 20 – calcite veins.

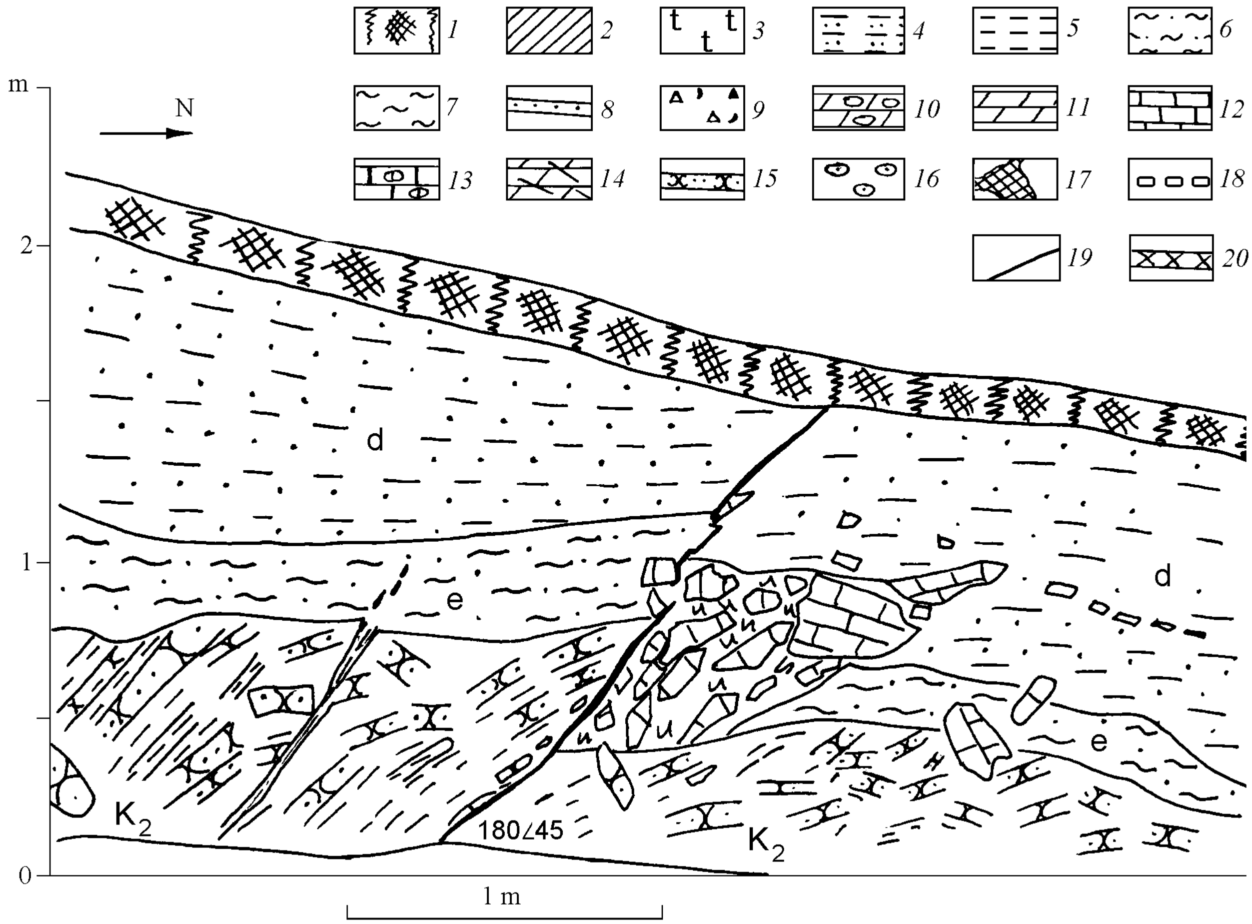

Figure 5. Sketch drawing of western wall of a trench across the active Kuznetsovsky fault (composed by E. A. Rogozhin). In the center, a debris wedge filled with limestone fragments is clearly seen.

11728), and samples collected from still older paleosol horizons, from 1.3–1.4, 2.0, and 2.2–2.3 m depths, yielded respective radiometric ages of 5210±200, 6840±230, and 8600±190 yr (IGAN-2429, IGAN-2417, and IGAN-2427).

The graben-like structure just described has, in all likelihood, a resonance-seismic origin. Albeit clearly confined to a specific rupture, it is not itself a surface expression of seismic fault. Hence, it cannot be classed as a primary seismotectonic rupture, as is the case with the Kuznetsovsky or Verkhnekhazarovsky faults (Figures 4, 5). The singular gravitationally unstable state of the southwestern limb of the Beregovoi fault, which is a tectonic block downthrown due to joint action of geologic and gravity-related, slope phenomena, rendered this block extraordinarily sensitive to seismic shocks. Apparently, any seismic shock that occurred nearby excited resonance oscillations in this unstable structure, each time causing a relatively small-magnitude (0.5–0.7 m), instantaneous gravitational displacement of the downthrown block in the southwest limb of the fault, extension, and sagging of the near-fault graben. Such sharp pulse displacements are recorded in the Holocene section filling in the graben as a sequence of alternating young loose sediments and paleosoils.

Periods of accumulation of soil horizons reflect phases of quiescence of the past gravitational-seismotectonic seismodislocation under study, whereas the overlying and intercalated talus/debris sequences record periods of renewed movements in the graben-like structure. This means that, based on these datings, seismic displacements occurred four times. The first occurred roughly between 9 and 7 ka; the second, between 7 and 5 ka; the third, between 5 and 3 ka; and, lastly, the fourth, between 3 ka and 100–170 (the modern soil age, IGAN-2418) or 250 (forest age) years ago. According to these results, the seismic shock that occurred in the year 1341±1 in the Malobzhidsky fault zone not far from the small graben is coeval with the last paleo-earthquake, just as the September 16, 1799 shock, related to the Verkhnekhazarovsky fault zone. Possibly, prior to these four seismic events, a yet another shock—the oldest of those recorded stratigraphically—took place in the late Pleistocene or early Holocene. Temblor of the graben-like structure at this shock gave rise to a minor debris wedge in the downfaulted, northeastern limb of the buried ancient scarp in the central part of the graben, in the base of the oldest paleosol horizon (Figure 6). Probably, two of the four ancient seismic events can be correlated to pulse displacements that left traces in the

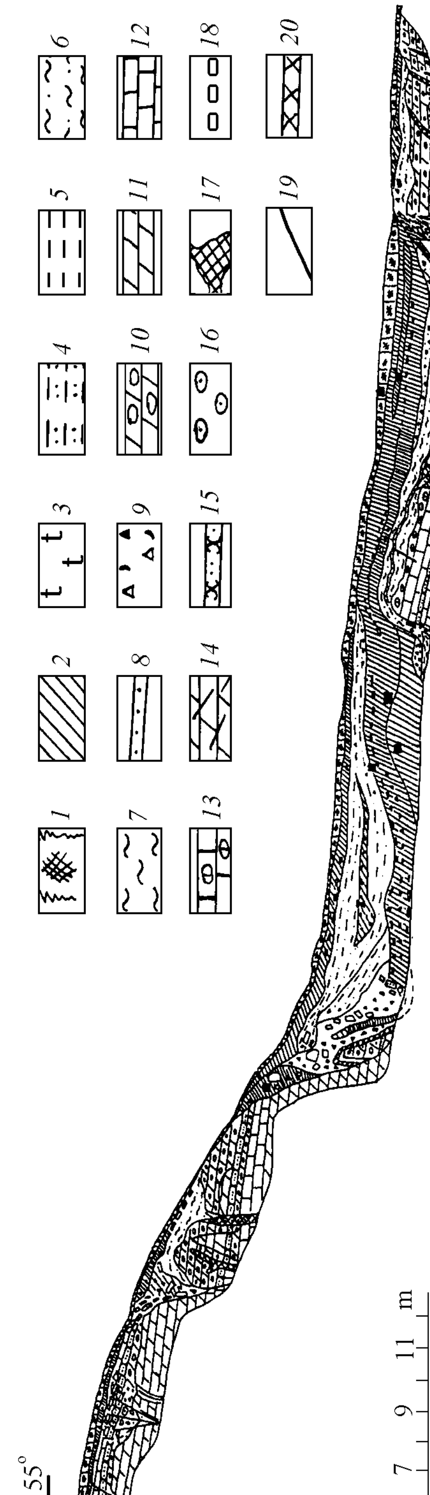

Figure 6. Cross section through a small graben developed in the Beregovoi fault zone, studied in southeastern wall of a trench (composed by E. A. Rogozhin, A. N. Ovsyuchenko, E. A. Ushanova, A. V. Marakhanov, and N. A. Dvoretskaya). Solid squares, localities sampled for radiocarbon dating.

Figure 7. Photograph of the trench depicted in Figure 6 (taken by N. I. Ovsyuchenko).

stratigraphy of the trenched Kuznetsovsky fault zone (Figure 5).

The recurrence period of major earthquakes in seismogenic zones of the south slope of the Northwest Caucasus, as deduced from these paleoseismologic data, is ca. 2000 years.

Within three highly active fault zones, we also managed to evaluate the rate of slow movement (creep) on individual faults and the amount of such movement over the past 100–300 or even 50 years (the period of formation of the modern soil and technogenic layer). Immediately within each fault zone, perceptible variations in the thickness of modern soil are observed. Thus, in the Verkhnekhazarovsky fault zone, soil thickness ranges from 5–10 cm near individual ruptures to 40–50 cm over undisturbed tracts. Here, soil age is between 180±30 yr (IGAN-2120) and 280±30 yr (IGAN 2119). In the vicinity of fresh ruptures of the Kuznetsovsky fault, modern soil thickness is 10–12 cm, and in undisturbed areas, 30–35 cm. Radiometric (^{14}C) age of soil is 120±30 yr (IGAN-2125) here. In the Drovyanoi fault zone (Figure 8), soil has technogenic character and is ca. 40–50 years old (GIN-11729 and GIN-11730). The magnitude of the sharp, stepwise change in the thickness of this soil in the rupture zone is ca. 10 cm.

Hence, in all three cases, the rate of creep displacements on faults is between 1.5 and 2.0 mm/yr. These values are appreciably lower than those given by *Trifonov* [1999] for highly active Eurasian faults (5 mm/yr or more) or than the maximum rate of modern vertical crustal movements estimated from direct geodetic measurements (up to 6 mm/yr for the Caucasus region) [*Kuznetsov et al.,* 1997; *Lilienberg and Yashchenko,* 1989, 1991], but they are roughly equal to the values given for the Northwest Caucasus in the Map of Modern Vertical Movements [*Map...,* 1986].

Conclusions

Paleoseismologic studies in the Greater Caucasus, conducted in recent years and previously [*Paleoseismogeology...,* 1979; *Rogozhin and Ovsyuchenko,* 2001; *Rogozhin et al.,* 2001], show large earthquakes that left well-marked surface seismic ruptures to have occurred in the past in some geologically active fault zones. The study of past seismodislocations in trenches enabled us to constrain the age of ancient earthquakes. Recurrence interval of such seismic events in the Northwest Caucasus is on the order of 2000 years. The rate of geologic displacements (creep) on faults, based on radiocarbon dating of modern soils, is assessed at 1.5 to 2.0 mm/yr over the past 100 years.

Acknowledgments. This work was supported by the Russian Foundation for Basic Research (project nos. 00-05-96034, 01-05-65340, and 02-05-64946).

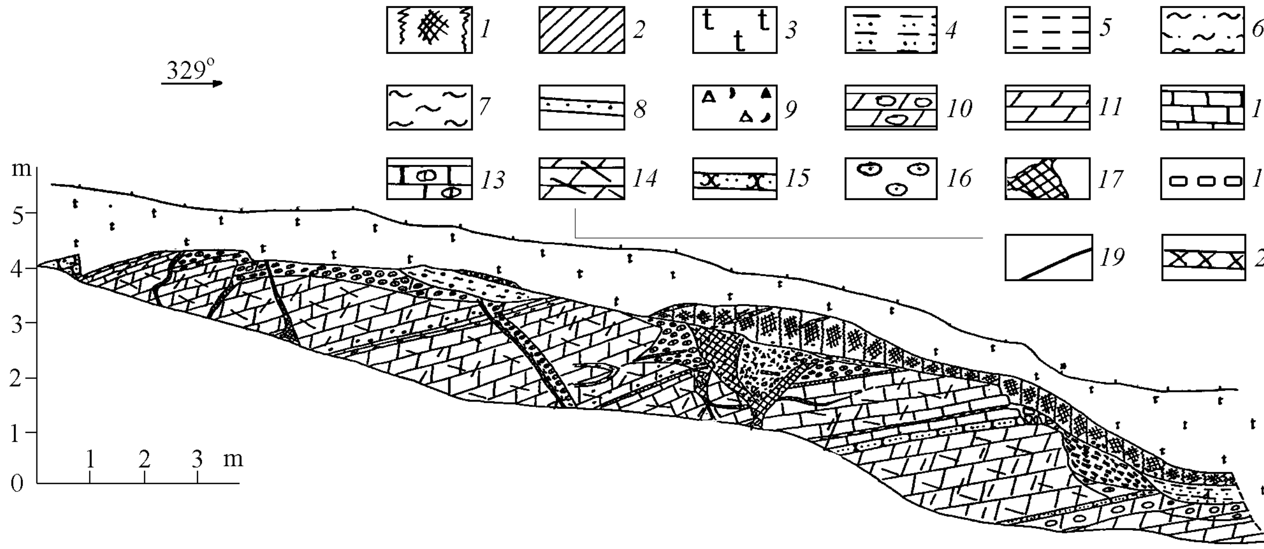

Figure 8. Sketch drawing of southwestern wall of a trench across the Drovyanoi active fault (composed by E. A. Rogozhin, A. N. Ovsyuchenko, E. A. Ushanova, A. V. Marakhanov, and N. A. Dvoretskaya). In the center, a small scarp on the base of the modern anthropogenic ("technogenic") layer above a fault branch is clearly seen.

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(Received 6 May 2002)