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Geostructural basis and geophysical investigations for the seismic hazard assessment and prediction in the Caucasus (*)

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Summary. — This paper deals with neotectonics, seismic hazard, and earthquake prediction in the Caucasus, a very active region of the Alps-Himalaya collisional system. The aim is to propose the territory of Georgia as a test area for seismic hazard assessment and earthquake prediction in the Caucasus. The active northward advance of the Arabian Plate to the central Caucasian sector of the Mediterranean mobile belt on the neotectonic stage gives rise to specific structures of reoriented folds, longitudinal squeezing and strike-slip faults. In the most compressed sector of the Caucasus arises a whole system of deep faults of different direction and order. Important parameters of such active faults have been reported in a catalogue together with their numerical expression of trustworthiness and degree of importance for seismic hazard assessment. Precursor studies have also been carried out in the same area. The orientation of the maximum compressive stress axis (established from regional and detailed structural analyses), the recent kinematics of active faults (obtained from earthquake fault plane solutions), and results of direct measurements of the Earth's crust displacement (GPS technology) show on the whole a submeridional compression of the region and corroborate the opinion of continuing underthrusting of the Transcaucasian plate under the Greater Caucasus (continental subduction). In the plate situated east of the Tskhinvali-Kazbegi left lateral strike-slip fault, the compression has direction changed to NE. Neotectonic vertical movements, revealed on the basis of planation surface analysis, include mainly the Greater Caucasus and the Adjara-Trialeti fold zone of the Lesser Caucasus. A seismotectonic map of the Caucasus showing active faults and epicentres of earthquakes occurred during the last century and the main historical events reveal the main patterns of seismicity in this region. Daily averaged tilt component data recently obtained at the Varzia tilt site in the southern Caucasus revealed intermediate-term creep-related ground tilts of preseismic origin which implement the above-mentioned structural investigation results. These tilts are also considered in the seismic hazard assessment since they were precursors of the Javakheti earthquake of December 16, 1990 ($M = 4.7$). An interpretation of such precursors includes tilt and strain fields slowly propagating from the preparation

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focal area to the measurement site. This propagating front activates oscillations of blocks which are regulated by the rheological properties of the fault materials.

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1. – Introduction

The Caucasus is located in a seismoactive zone of the central part of the Mediterranean orogenic domain, as is confirmed by manifestations of both historical and recent strong earthquakes with devastating effects. In the countries of the former Soviet Union (FSU), where the quality of constructions was low and insurance mechanisms not adjusted, strong earthquakes may cause relevant consequences. Even now, Armenia and Georgia are far from recovery after the destructive Spitak and Racha earthquakes of December 7, 1988 ($M = 6.9$) and April 29, 1991 ($M = 7.0$), respectively. At the same time the hazard increases every year due to the growth of population and the increasing number of seismically vulnerable buildings and industrial manufactures.

This paper deals with the territory of Georgia as a test area for seismic hazard assessment and earthquake prediction in the Caucasus. Although there are some publications about the Caucasus region in English language, most of the geological and geophysical works done by Georgian researchers are published in Russian or in Georgian, and they are in many cases not easily accessible. Therefore, this paper will also give a contribution in this sense.

Because of the limited time-scale of instrumental seismology and the large recurrence intervals of seismic events in the areas of continental collision as the Caucasus, we should use more intensely the tools of modern tectonics in seismic hazard assessment. Therefore Georgian geologists and specialists in tectonics have been recently working in this direction. First of all, they examined the character of neotectonics and recent deformation of the Caucasus and adjacent areas on the basis of paleomagnetic and paleokinematic data and with the application of regional and detailed structural analysis [1,2]. At the same time, a continuous tilt monitoring of a specific area of the region has been carried out in order to reveal earthquake precursors.

Here, an active fault map of the Caucasus, constructed on the basis of different geological and geophysical data, is presented. A catalogue and a map of active faults, stress tensor orientations map and maps of horizontal and vertical movements of the Earth's crust of the neotectonic stage and of the present day as well are also compiled (at the beginning, the scale of all maps was 1:500 000).

The directions of horizontal movements is corroborated with first data obtained from GPS technology. Also creep-related tilt precursors obtained from a continuous ground tilt monitoring are presented. We believe that this material along with analogous data for the Caucasus as a whole, the comparisons with other regions having similar tectonics, and the continuous monitoring of geophysical fields of fundamental interest (such as ground tilt and strain) in some sites of the region, create a favorable basis for the seismic hazard assessment and earthquake prediction of the Caucasus.

Previous studies [3] concerning pattern recognition of earthquake-prone areas in Italy allowed the identification of the intersections of lineaments where strong earthquakes may be expected to occur. Specifically, it was observed that the earthquake-prone areas of Italy are characterized by high elevation. These results were in sound agreement with those for the Pamir and Tien-Shan [4]. The same studies also reveal that favorable similarities seem to exist between the Central Apennines in Italy and the Southern Caucasus in Georgia [5].

2. – Geological and structural setting of the Caucasus

The Caucasus has undergone a long and complicated geologic evolution and, at present, it is constituted by many geologic structures of different character, order and

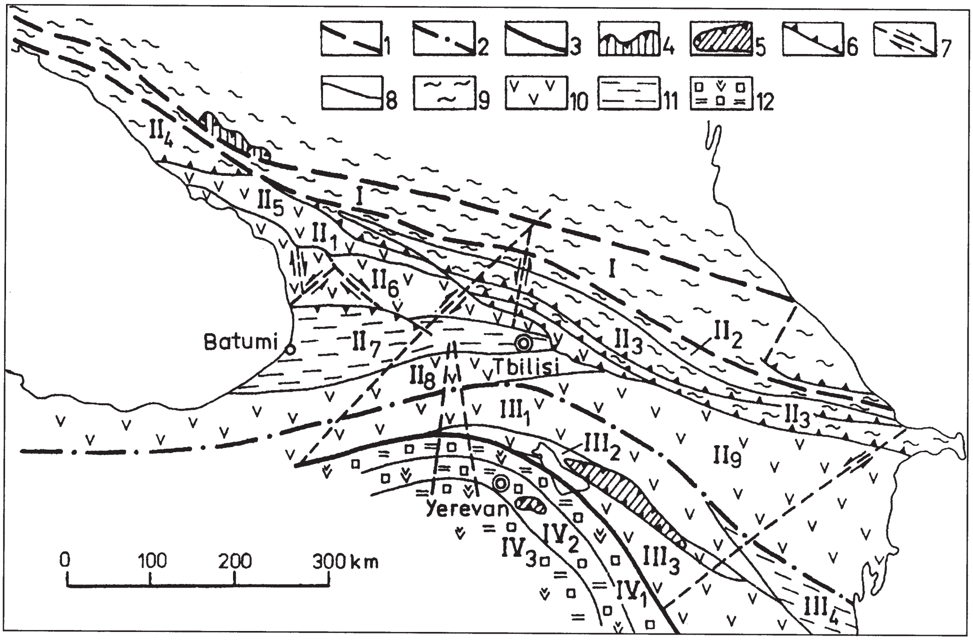

Fig. 1. – Tectonic zoning of the Caucasus on the basis of the terrane analysis (after Gamkrelidze, [7]). Displacement terranes of the first order and subterranes: I: Greater Caucasian terrane; II: Black Sea-Centraltranscaucasian terrane; Subterranes: II_1: Chkhalta-Laila, II_2: Kazbegi-Tphani, II_3: Mestia-Dibrar, II_4: Novorosiisk-Lasarevskoe, II_5: Gagra-Java, II_6: Dzirula, II_7: Adjara-Trialeti, II_8 Artvin-Bolnisi, II_9: Middle and lower Kura; III: Baiburt-Sevanian terrane. Subterranes: III_1 Somkheto-Karabakh, III_2 Sevan-Akera, III_3: Kafan, III_4: Talish; IV: Iran-Afghanian terrane. Subterranes: IV_1: Miskhan-Zangezur, IV_2: Erevan-Ordubad, IV_3: Araks. 1-3 ophiolite sutures (here and there presumable), marking the location of small and large oceanic basins of: 1 Late Precambrian(?)-Paleozoic age: 2 Paleozoic-Early Mesozoic age, 3 Mesozoic-Early Cenozoic age; 4-5 ophiolite terranes (obduction sheets): 4 Paleozoic age, 5 Mesozoic age; 6 detached cover nappes; 7 transterrane and interterrane strike-slip and transverse faults; 8 border of subterranes (deep faults). Geodynamic conditions in Mesozoic-early Cenozoic. 9-11 West Pacific type active continental margin: 9 marginal sea (pelagic sediments, turbidites, submarine tholeiite-basaltic volcanites), 10 island arc (shallow-marine sediments and submarine volcanites of calc-alkaline composition), 11 intra-arc rift (pelagic sediments, tephro- and sandstone turbidites, tholeiitic and shoshonitic mainly basaltic submarine volcanites); 12 microcontinental (of passive margin type in Mesozoic with shallow-marine sediments and of the Andean type active margine in Cenozoic with calc-alkaline submarine volcanites).

genesis. Its geologic evolution is closely related to the development of a vast area of the Earth's lithosphere; therefore it is usually considered against the background of the entire central segment of the Mediterranean mobile belt and adjacent regions. At the same time, paleokinematic and paleomagnetic methods, along with the traditional geological ones (character of sedimentation, magmatism and geology of ophiolites, paleoclimatic and paleogeographic data), are crucial in the modern approach to this problem and to the interpretation of the Earth's lithosphere present structure [1].

The tectonic zoning of the Caucasus and of the entire central segment of the Mediterranean belt is carried out on the basis of all the above-mentioned data and of the terrane analysis [6], that is also widely used for the tectonic zoning of the Pacific continental margins.

Within the central segment of the Mediterranean mobile belt, one can distinguish displaced terranes (that we will call here of the first order), most of which are composite. They are: the Greater Caucasian, the Black Sea-Centraltranscaucasian, the Baiburt-Sevanian, the Anatolian and the Iran-Afghanian terranes [6]. During the Paleozoic, Mesozoic and Early Cenozoic times these microplates underwent horizontal displacement in different directions within the oceanic area of Proto-, Paleo-, Meso- and Neotethis at a distance as a rule exceeding the horizontal extent of the terranes themselves. As a result of early Cimmerian, Bathonian (Adygean), Austrian (mid-Cretaceous), Subhercynian (mid-Senonian) and Pyrenean (late Eocene) orogenic phases the terranes were consecutively joined to the Eurasian continent [1, 6].

Figure 1 shows the tectonic map of the Caucasus on the basis of the terrane analysis. In the scheme one can see displaced terranes of the first order, composed of different subterranes. Besides, the geodynamic conditions in the Caucasian region during the Mesozoic and Early Cenozoic time are also shown.

3. – Neotectonic deformation of the Mediterranean belt central segment and deep faults of the Caucasus

The bulk of material obtained in recent years defining paleolatitudes of the continental framework of the central segment of the Mediterranean belt, as well as those of separate continental microplates (terranes) within its limits, is of great interest. This material gives not only qualitative but also quantitative characteristics of horizontal displacement of the Earth's crust [1].

Proceeding from the topic of this paper, only two stages of the palinspastic reconstructions of the central segment of the Mediterranean belt are given: the Late Senonian and the Eocene time (fig. 2). Since the Eocene onset time of continental collision, one can observe convergence of Afro-Arabian and Eurasiatic plates. Till the orogenic stage, the central segment of the Mediterranean belt with northwesterly strike underwent transverse compression. But since the orogenic stage, as we shall see later, the main dynamic processes in the Caucasus sector of the Mediterranean belt were determined by an active northward advance of the Arabian plate. The formation of a complex structure of this sector is connected with the horizontal compression of the Earth's crust. It corroborates the detailed and regional structural analysis of the Caucasian tectonic structures. In particular, according to the up-to-date studies, the fold structure of the Greater Caucasus was formed as a result of intense deep-seated compression, which was mainly caused by the advance of the relatively rigid Georgian Block (Dzirula subterrane) and its underthrusting beneath the Greater Caucasus [7].

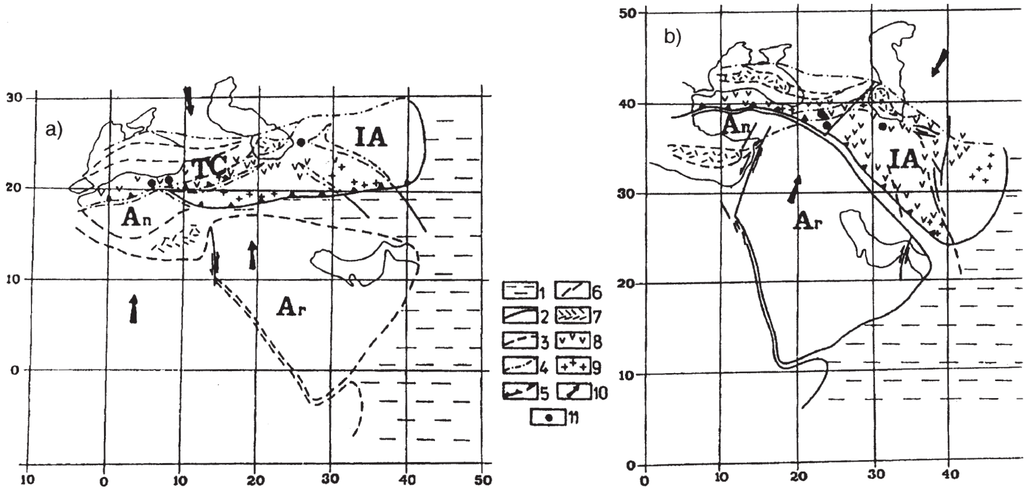

Fig. 2. – Palinspastic reconstructions of the central segment of the Mediterranean belt for the Late Senonian (a) and for the Eocene (b) (after Gamkrelidze, [1]). 1 oceanic area; 2-3 boundaries of continental plates with definite position: 2 by paleomagnetic data, 3 presumably; 4 collision sutures and boundaries of intercontinental (ensialic) structures; 5 subduction zones; 6 faults; 7 relic oceanic basins and extinct rifts with suboceanic crust; 8 calc-alkaline volcanics; 9 granitoid magmatism; 10 direction of relative movements; 11 point of the average meanings of the paleolatitudes. Microcontinents: TC: Transcaucasian, An: Anatolian, Ar: Arabian, IA: Iran-Afghan.

Such a mechanism gives the only acceptable explanation of the distinctly expressed asymmetry of the Greater Caucasus, of the development of southerly vergencial isoclinal folding and of southerly directed large nappes on its southern slope. So, along the southern margin of the Greater Caucasus one can see [8] the manifestation of continental subduction (Amstutz-type subduction).

A problem of great interest is also the development of Late Alpine, mainly ophiolite nappes framing Arabia (South Taurus, Iskenderun zone and Zagros), whose formation, beginning in the Subhercinian (mid Senonian) phase, is associated with the advance of the Arabian plate to the north and its subduction beneath the formed fold systems.

However, in the section located next to the north of the Arabian wedge, mainly in the central and western parts of the Caucasus, a number of interesting geological events have been detected. First of all, the occurrence of deformed fold structures that are characterized by the following morphological features: festoony forms of the fold ends, S-like curvature of their axes, dome-shaped forms of anticlines and cup and through-like forms of synclines. In order to investigate the fold deformation peculiarities during the second compression of the primary folds, a series of tectonic experiments have been carried out. As a result, all morphological varieties of transformed fold structures traced in this region have been obtained [9]. Of particular importance is the gradual rejuvenation of the process of fold transformation. So, in the Somkheto-Karabach subterrane the pre-Early Cretaceous folds, beginning at the Laramian (pre-Paleogene) folding phase, undergo transformation. In the Adjara-Trialetian zone, folds formed in the Laramian phase transform as a result of Late Pyrenean (pre-Upper Eocene) and younger phases. On the Georgian Block (Dzirula terrane) newly formed, sublatitudinal and other folds belong to the Attic-Rhodanian (Miocen and pre-Pliocene) and even younger phases. The process of fold transformation, within the boundaries of the North-Western Caucasus and in the Abkhazia folds, is also young (post-Paleogene). Thus, this rejuvenation of transformation (reorientation) reflects the advance of the Arabian plate to the north along the submeridional direction during the orogenic stage.

Among the largest strike-slip faults, that arose in the orogenic stage, the well-known Tskhinvali-Kazbegi and Palmir-Apsheron sinistral faults are to be mentioned. A very young (Late Quaternary) dextral displacement is traced along the zagros suture [10]. Similar movements are also observed along some longitudinal faults, particularly along the North Anatolian and, less important, along the southern edge of the Elburs and Aladag-Binalud. These movements are connected with the squeezing of masses from the most compressed Caucasus sector of the Mediterranean belt. In the Caucasus sector there emerges a whole system of principal seismogenic structures constituted by deep faults having different direction, that continue to develop at present.

As mentioned above, in the Caucasus, faults of the first order are ophiolite sutures, marking terrane boundaries. They completely meet the requisites of deep faults. As generally known, deep faults are characterized by three main features: large extent,

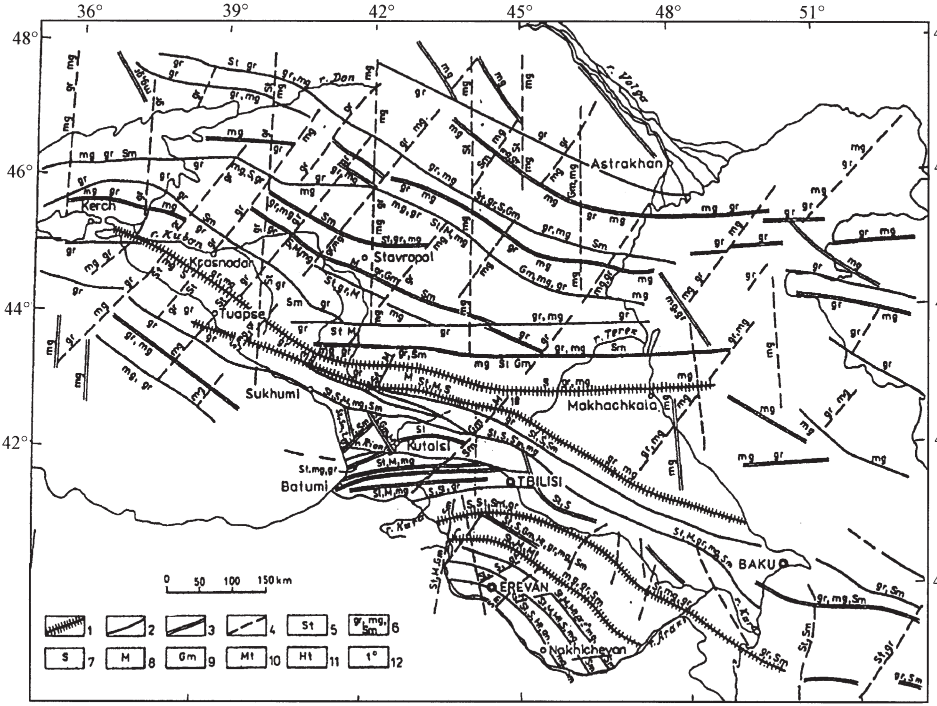

Fig. 3. – Scheme of deep faults of the Caucasus (after Gamkrelidze *et al.*, [11], with changes). 1-4 situation of faults with respect to tectonic units of the Caucasus: 1 ophiolite sutures (here and there presumable), marking terrane boundaries, 2 deep faults situated between tectonic zones (subterranes and blocks), 3 within the zones, 4 transzonal; 5-12 signs of faults existence: 5 structural, 6 geophysical (gravimetric, magnetic, seismic), 7 sedimentation, 8 magmatic, 9 geomorphic, 10 metamorphic, 11 hydrothermal alteration of rocks, 12 exposure of thermomineral springs.

considerable depth of penetration and long period of development. The existence of deep faults, that in many cases are overlain by sediments of different thickness, has been established on the basis of structural, sedimentary, magmatic, geomorphic, and hydrogeologic data, other than taking into account different geophysical signs (gravimetric, magnetic, seismic and others). Only certain aggregates of signs give an opportunity of their trustworthy identification. Just proceeding from this principle, a scheme of deep faults of the Caucasus was composed (fig. 3) [11]. We used here concepts such as morphostructural zoning together with those that take into account lateral motions (*e.g.*, the concept of "terranes"). This is not a mixture of different incompatible concepts. The morphostructural zoning reflects the contemporary structure of the Caucasus, which now consists of "accretionary terranes" separated by ophiolitic sutures, whereas in the geological past the terranes were separated by a vast oceanic basin of Proto-Paleo, Meso- and Neotethis. This is indicated by palinspastic reconstructions based on paleomagnetic data. The terranes had a different geodynamic nature (island arc, microcontinent, etc.). During the Late Paleozoic, Mesozoic and Early Cenozoic, they were consecutively joined to the Eurasian continent, the south margin of which (central and northern parts of the Caucasus) represented a continental margin of west-Pacific–type. In the contemporary structure, as a result of intensive postaccretionary compression, ophiolitic sutures as well as deep faults within the terranes are subvertical or have steep inclination and the ophiolites of different age are squeezed out and obducted from it. They overthrust both on the continental margin and on the various terranes. At the same time, as a result of overthrusting or underthrusting during accretion or collision, terranes and subterranes overlapped each other at a great distance (tens of kilometres or more). For instance, frontal lines of such overlapping traced along the southern margin of the Greater Caucasus and the northern margin of the Lesser Caucasus (see figs. 4 and 8 below).

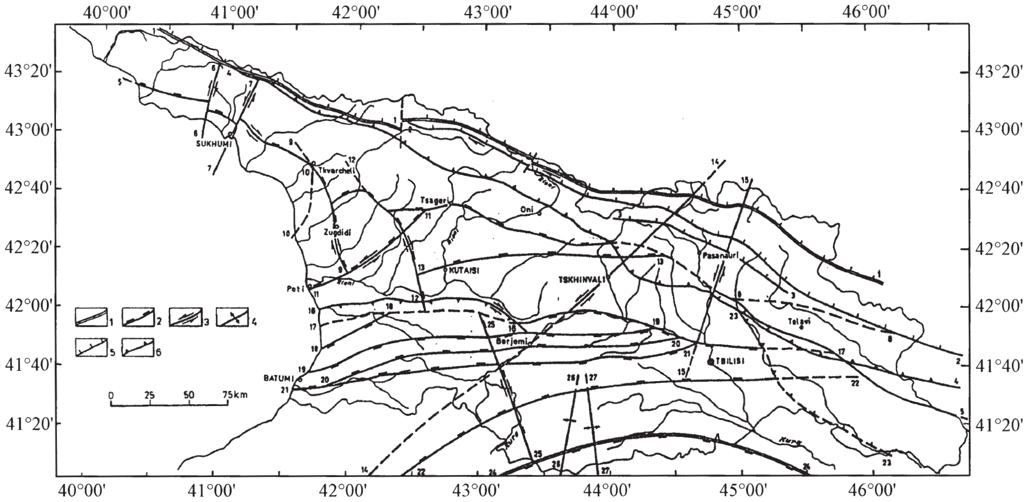

Fig. 4. – Map of active deep faults of the territory of Georgia (authors: I. Gamkrelidze, T. Giorgobiani, S. Kuloshvili, G. Lobzhanidze). 1 faults marking terrane baundaries (presumable ophiolite sutures); 2-3 other overlapped (hidden) deep faults: 2 reversed faults, 3 strike-slip faults; 4-5 deep faults exposure on the Earth's surface: 4 regional thrusts, 5 fronts of overthrust nappes. For the appelation of faults see the catalogue (table II).

4. – The territory of Georgia as a test area for seismic hazard assessment and earthquake prediction in the Caucasus

4·1. *Active faults map and catalogue.* – Active faults are studied in detail in the territory of Georgia (fig. 4). Lately it turned out that a number of faults had not to be considered as typical deep ones. In particular, the southern marginal faults of the flysch zone in the southern slope of the Greater Caucasus, the so-called Orkhevi and Svaneti faults that were traced along the southern edge of the Svaneti uplift (Mestia-Tianeti subterrane), formerly had been considered as exposure on the surface of deep faults. But recent investigations have shown [12] that both faults correspond to the frontal thrust of the nappe complex belonging to the southern slope of the Greater Caucasus (fig. 4). It is also impossible to attribute to the category of deep faults the northern marginal fault of the Adjara-Trialeti zone, in its western part, as well as the fault limiting this zone from the east. Both faults are frontal overthrusts of the nappe structures.

Within Georgia, major faults are mainly developed between tectonic units of different order. They have basically north-eastern or latitudinal strike. Some faults developed within the zones have similar strikes too. All of them are characterized by long development and were born on extensional stages of evolution of the Caucasus region. These are: Middle Paleozoic, Early and Middle Jurassic, Early and Middle Cretaceous, beginning of the Eocene and Late Pliocene times. On the orogenic stage of development under existing intense compressional conditions, almost all of these longitudinal deep faults turn into reversed faults, thrust faults or overthrust nappes.

The faults of transverse strike (submeridional and diagonal) were born mainly in the orogenic stage. Some of them are developed within separate tectonic zones or distinctly through faults. Besides, NNE-oriented faults correspond to left-lateral strike-slip fault zones, NNW-oriented ones correspond to right-lateral strike-slip fault zones. Faults of submeridional direction are also through faults and were born on the maximum compression stage of the Caucasus. They represent the huge cross-joint on which new volcanic centres are situated.

The majority of the above-mentioned faults are buried ones overlain by sediments. An exception is constituted by regional thrusts and frontal thrusts of the nappes. They are manifested on the surface as flexures, en echelon folds, or as clusters of regional faults. Some of them were affected by basic volcanic activity and had deep penetration. Sedimentation signs show in many cases the long development of faults.

All deep faults are displayed as geophysical lineaments. According to works carried out with the help of seismic, gravimetric, and magnetic methods, a scheme of probable faults of Georgia was composed (fig. 5). According to data of the correlation method of refracted waves, possible faults were revealed on the surface of the crystalline basement, which in Georgia lies within 15 km depth.

In the sedimentary cover and on the surface of Jurassic, Cretaceous, Eocene and Meotic sediments, probable faults were established on the basis of different modification data of reflection shooting.

By means of the deep seismic sounding method, probable faults were distinguished in the Volgograd-Nakhichevan and Anaklia-Akstafa regional profiles. Probable faults were outlined on gravimetric maps of high precision (scales 1 : 50000, 1:100000, and 1:200000) in stripes of increasing gradients (in gravitational lineaments). For the revealing of faults with the help of magnetic methods of exploration, the following data were used: positive magnetic anomalies of linear form (which apparently indicate the possible filling of fault zones with magmatic rocks of high magnetic properties), a chain

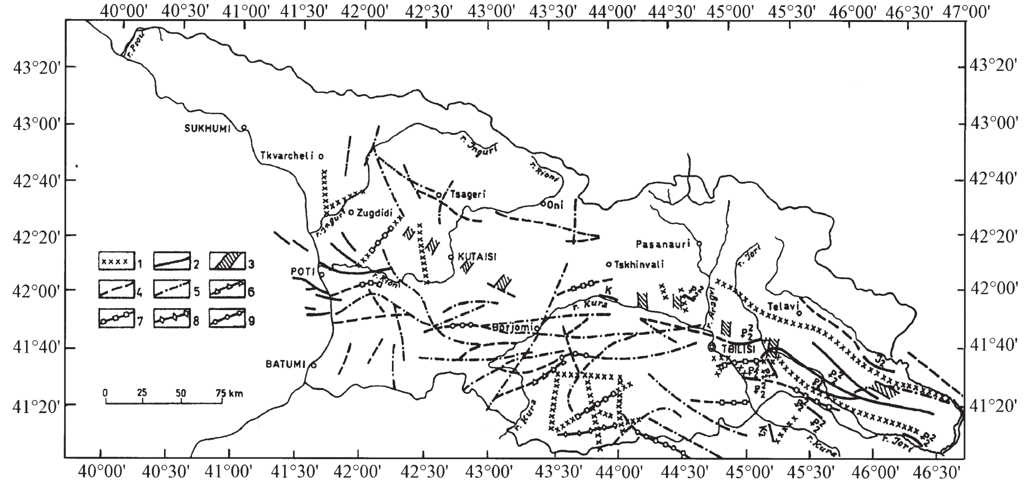

Fig. 5. – Scheme of probable faults of the territory of Georgia according to exploration geophysics data (scientific editors: B. Balavadze, G. Shengelaia; authors N. Gamkrelidze, Sh. Diasamidze, A. Rusadze, O. Sepashvili, A. Svanadze, N. Khvedelidze, G. Shengelaia). Faults revealed according to: 1 data of correlation method of refracted waves, 2 data of reflection shooting (with indication of a dislocated horizons age), 3 data of deep seismic sounding, 4 gravimetric data, 5 magnetic data, 6 seismic, gravimetric and magnetic data, 7 seismic and gravimetric data, 8 seismic and magnetic data, 9 gravimetric and magnetic data.

of magnetic anomalies, the existence in the fault zone of separate magmatic (magnetic) bodies, the existence of linear negative magnetic anomalies on the background of positive ones (fault zone filled by nonmagnetic rocks or the presence of a crush zone in which relic magnetizing is lost), the existence of stepped (high gradient zones) and displaced anomalies connected with the location of fault walls at a different depth.

In some places the faults are established on the basis of a combination of seismic, gravimetric and magnetic, seismic and gravimetric, seismic and magnetic, gravimetric and magnetic data.

The absence of faults here and there in the scheme of fig. 4 (for example on the southern slope of the Greater Caucasus) is caused by the absence of reliable geophysical data. At the same time the existence of the above-mentioned deep faults in the territory of Georgia testifies the presence of many clusters of earthquake epicentres connected with them. In most cases they are exhibited by means of aerogeologic data as well.

Naturally, the degree of reliability of fault ascertainment is higher when many different signs of their existence are present. But, as well as under any statistical investigation, the "degree of importance" of these signs should be defined. Therefore different signs, which characterize the hidden deep faults, are of different importance. According to the preliminary chosen scheme for the "degree of importance" of the signs for the fault's existence, one can distinguish more "ponderable" and less "ponderable" signs. For example, in our opinion the scheme of the "degree of importance" for faults tracing in the territory of Georgia may have the form reported in table I.

Summing up digits of the degree of importance of the signs, one has an opportunity to give a numerical expression to the fault trustworthiness (see the catalogue of faults reported in table II).

TABLE I. – *Scheme of the degree of importance of the fault's existence signs.*

Signs of fault's existence	Degree of importance
Geological	
structural (Str)	2
sedimentation (S)	3
magmatic (M)	2
geomorphic (GM)	1
boring data (B)	3
disposition of volcanic centres (VC)	2
hydrogeological (Hg) (exposure of thermomineral springs)	1
data of aerogeology (Ac)	1
Geophysical	
gravimetric (Gr)	1
magnetic (Mg)	1
seismic (Sm) (disposition of earthquake epicentres)	1
correlation method of refracted waves (Refr.)	2
reflection shooting (Refl.)	2
deep seismic sounding (DSS)	2
exchange waves method	1

At the same time, the catalogue of faults contains such important parameters as dip and azimuth of the fault plane, depth of penetration and of activity (on the basis of hypocenters data), kinematics of faults, magnitude of neotectonic and Quaternary vertical separation and horizontal throw, average rate of neotectonic and Quaternary displacement and average level ($\overline{A}_{3,3}$) of seismic activity. This was revealed by taking into account the mean quantity of seismic activity along the separate faults. Three intervals of activity level were considered: low ($\overline{A}_{3,3} \leqslant 0.05$), middle ($\overline{A}_{3,3} = 0.1$–$0.2$ and high ($\overline{A}_{3,3} \geqslant 0.05$).

In conclusion, signs as the seismic activity and average rates of neotectonic and Quaternary displacement, give an opportunity to judge the importance of each fault for seismic hazard assessment.

Also in this case, more "ponderable" and less "ponderable" signs should be distinguished. In particular, a possible scheme of the degree of importance of faults for seismic hazard assessment is reported in table III.

Summing up the above-mentioned parameters of faults, one obtains the numerical expression of the faults importance for seismic hazard assessment (table II).

An important fault parameter to be revealed is the width of the fault zone. As is generally known, the fault zone is a flat but three-dimensional body. The width of regional faults and frontal thrust zones can be established by means of direct field measurements. But, for the definition of the width of hidden deep faults, we are constrained to look for indirect ways, one of which is to find a mathematical correlation between different characteristics of the faults.

On the basis of special field investigations and analysis of data reported in the literature, Alioshin *et al.* [13] proposed special mathematical ratios between the width,

TABLE II. – *Catalogue of active faults of the territory of Georgia. (Authors: I. Gamkrelidze, T. Georgobiani, S. Kuloshvili, G. Lobjanidze.)*

N	Appellation of faults	Length (km)	Average dip azimuth and angle of fault plane	Depth of penetration (dp) and depth of activity (da) (km)	Kinematics	Presumable width of fault zone (km)	Neotectonic vertical separation (V) horizontal throw (H) (km)	Quaternary vertical separation (V) horizontal throw (H) (km)	Average neotectonic rates of displacement (mm/year)	Average quaternary rates of displacement (mm/year)	Level of seismic activity	Signs of existence	Degree of trustworthiness	Degree of importance for seismic hazard assessment
1	Main thrust of the Greater Caucasus	1000	NNE, <50–80°	$\frac{\mathrm{dp}>50}{\mathrm{da}=15\text{–}25}$	right-reverse-slip fault	17	$V=2.0$	$V=0.4$	0.2	0.4	3	Str, S, M, Gm, Sm, Ac	10	11
2	Gebi-Lagodekhi	750	NNE, <55–80°	$\frac{\mathrm{dp}=10\text{–}15}{\mathrm{da}=10\text{–}12}$	right-reverse-slip fault	10	$V=1.5$	$V=0.3$	0.15	0.3	3	Str, Gm, Sm, Hg	5	9
3	Chirici	110	NNE, <50–70°	$\frac{\mathrm{dp}=10\text{–}12}{\mathrm{da}=10\text{–}12}$	reverse-slip fault	4	$V=0.7$	$V=0.2$	0.07	0.2	2	Str, Sm	3	6
4	Frontal over-thrust of the Caucasus nappes	870	NNE, <0–70°	$\frac{\mathrm{dp}=5\text{–}6}{\mathrm{da}=?}$	nappe	17	$H=15\text{–}60$	$H=0$	0.5–2	0.1	2	Str, S, Gm, Ac, B	10	9
5	Gagra-Java	1200	NNE, <70–90°	$\frac{\mathrm{dp}>50}{\mathrm{da}=10\text{–}12}$	right-reverse-slip fault	15	$V=1.5\text{–}3.5$	$V=0.5\text{–}0.8$	0.15–0.25	0.5–0.8	2	Str, S, M, Gm, Refr, DSS, Gr, Mg, Ac, B	18	13
6	Akhali Athoni	60	NNE, <80–90°	$\frac{\mathrm{dp}=5\text{–}6}{\mathrm{da}=?}$	right-normal-slip fault	2	$H=4\text{–}5$	$H=1.5$	0.4	0.4	1	Str, Gm	3	10
7	Gumista	60	WSW, <80–90°	$\frac{\mathrm{dp}=5\text{–}6}{\mathrm{da}=5\text{–}6}$	left-normal-slip fault	2	$H=3\text{–}4$	$H=1.2$	0.3	0.4	1	Str, Gm	3	10
8	Akhmeta-Lagodekhi	180	SSW, <80–90°	$\frac{\mathrm{dp}=5\text{–}6}{\mathrm{da}=?}$	normal-slip fault	6	$V=0.7$	$V=0.5$	0.07	0.5	2	Str, S, Gm	6	9
9	Tskhakaia-Tsaishi	50	ENE, <60–70°	$\frac{\mathrm{dp}=10\text{–}12}{\mathrm{da}=10\text{–}12}$	right-reverse-slip fault	2	$V=1.0$	$V=0.4$	0.1	0.4	2	Str, Gm, Sm	4	9

TABLE II (*Continued*).

N	Appellation of faults	Length (km)	Average dip azimuth and angle of fault plane	Depth of penetration (dp) and depth of activity (da) (km)	Kinematics	Presumable width of fault zone (km)	Neotectonic vertical separation (V) horizontal throw (H) (km)	Quaternary vertical separation (V) horizontal throw (H) (km)	Average neotectonic rates of displacement (mm/year)	Average quaternary rates of displacement (mm/year)	Level of seismic activity	Signs of existence	Degree of trustworthiness	Degree of importance for seismic hazard assessment
10	Achigvara	60	E, <80–85°	$\frac{dp=8\text{–}10}{da=8\text{–}10}$	left-reverse-slip fault (?)	2	$V=0.5$	$V=0.1$	0.05	0.1	1	Sm Refr., Ac	4	3
11	Poti-Abcdathi	70	NNW, <60–80°	$\frac{dp=10\text{–}12}{da=10\text{–}12}$	left-reverse-slip fault	2	$V=1.2$	$V=0.4$	0.12	0.4	2	Str, S, DSS, Sm, Refr., Hg, Ac, B	15	9
12	Vartsikshe-Gegechkori	75	NNE, <75–85°	$\frac{dp>50}{da=10\text{–}12}$	right-reverse-slip fault	2	$V=1.5$	$V=0.5$	0.15	0.5	2	Str, M, Sm, Hg, Refr.	8	10
13	Kutaisi-Sachkhere	130	N, <80–90°	$\frac{dp=10\text{–}15}{da=10\text{–}15}$	reverse-slip fault	7	$V=1.2$	$V=0.5$	0.12	0.5	2	Str, M, Sm	5	10
14	Tskhinvali-Kazbegi	1350	NW, <80–90°	$\frac{dp>50}{da=15\text{–}20}$	left-reverse-slip fault	16	$H=4$	$H=1.3$	0.2	1.3	2	Str, M, Sm, Mg, Ac, Vc	7	13
15	Assa-Aragvi	110	WNW, <85–90°	$\frac{dp=10\text{–}12}{da=?}$	left-lateral-slip fault	2	$H=5$	$H=1.5$	0.2	0.5	1	Str, S, Ac	6	10
16	Northern marginal over thrust of Adjara-Trialeti	160	S, <10–40°	$\frac{dp=3\text{–}4}{da=3\text{–}4}$	nappe	5	$H=10\text{–}15$	$H=0$	0.5	0.1	1	Str, Gm, Ac, B	9	7
17	Northern marginal of Adjara-Trialeti zone	500	S, <70–85°	$\frac{dp>50}{da=15\text{–}20}$	reverse-slip fault	12	$V=2.0$	$V=0.1$	0.05	0.1	2	Str, S, M, Gm, Sm, Gr, Mg	11	4
18	Chokhatauri	85	SE, <75–85°	$\frac{dp>50}{da=15\text{–}20}$	reverse-slip fault	4	$V=1.5$	$V=0.3$	0.15	0.3	2	Str, S, M, Gm, Gr, Mg, Sm	11	8

TABLE II (*Continued*).

N	Appellation of faults	Length (km)	Average dip azimuth and angle of fault plane	Depth of penetration (dp) and depth of activity (da) (km)	Kinematics	Presumable width of fault zone (km)	Neotectonic vertical separation (V) horizontal throw (H) (km)	Quaternary vertical separation (V) horizontal throw (H) (km)	Average neotectonic rates of displacement (mm/year)	Average quaternary rates of displacement (mm/year)	Level of seismic activity	Signs of existence	Degree of trustworthiness	Degree of importance for seismic hazard assessment
19	Northern axial of Adjara-Trialeti zone	250	S, <80–90°	$\frac{\mathrm{dp} > 50}{\mathrm{da} = 10\text{–}12}$	reverse-slip fault	7	$V = 1.3$	$V = 0.4$	0.13	0.4	2	Str, S, M, Gr, Mg, Sm	10	9
20	Southern axial of Adjara-Trialeti zone	220	N, <80–90°	$\frac{\mathrm{dp} > 50}{\mathrm{da} = 10\text{–}12}$	reverse-slip fault	7	$V = 1.1$	$V = 0.4$	0.11	0.4	2	Str, S, M, Sm, Ac	9	7
21	Adjara-Tskali-Tedzami	350	N, <75–85° S, <70–85°	$\frac{\mathrm{dp} = 5\text{–}6}{\mathrm{da} = 5\text{–}6}$	reverse-slip fault	9	$V = 1.0$	$V = 0.3$	0.1	0.3	2	Str, S, Exw, M, Mg	9	7
22	Southern marginal of Adjara-Trialeti zone	600	N, <80–90°	$\frac{\mathrm{dp} > 50}{\mathrm{da} = 15\text{–}20}$	reverse-slip fault	13	$V = 1.0$	$V = 0.3$	0.1	0.3	2	Str, M, Exw, Sm, Gr, Ac	8	7
23	Frontal overthrust of molasse nappe	190	NE, <10–40°	$\frac{\mathrm{dp} = 3\text{–}4}{\mathrm{da} = 3\text{–}4}$	nappe	6	$H = 10\text{–}15(?)$	$H = 0$	0.5	0.1	2	Str, Sm, Mg, Ac, Refr., Refl., B	12	8
24	Loki-Agdam	750	S, <75–85°	$\frac{\mathrm{dp} > 50}{\mathrm{da} = 15\text{–}20}$	reverse-slip fault	15	$V = 1.5$	$V = 0.3$	0.15	0.4	2	Str, S, Sm, Exw, Gr, Mg, Refr., Ac	12	9
25	Tmogvi-Atskuri	100	ENE, <80–90°	$\frac{\mathrm{dp} = 15\text{–}20}{\mathrm{da} = ?}$	right-reverse-slip fault	2	$V = 0.9$	$V = 0.2$	0.09	0.2	1	Str, S, M, Mg	8	5
26	Abul-Samsari	400	WNW, <85–90°	$\frac{\mathrm{dp} > 50}{\mathrm{da} = 10\text{–}12}$	tension fault	5	$H = 2\text{–}5(?)$	$H = 0.4\text{–}1.5(?)$	0.4(?)	0.8(?)	3	M, Sm, Mg, Vc	6	16(?)
27	Kechuti	250	WNW, <85–90°	$\frac{\mathrm{dp} > 50}{\mathrm{da} = 10\text{–}12}$	tension fault	4	$H = 2\text{–}5(?)$	$H = 0.4\text{–}1.5(?)$	0.4(?)	0.8(?)	3	M, Sm, Mg, Refr., Vc	8	16(?)

TABLE III. – *Scheme of the degree of importance of faults for seismic hazard assessment.*

Characteristic of fault	Degree of importance for seismic hazard assessment
Level of seismic activity	
$\bar{A}_{3,3} \leqslant 0.05$	1
$\bar{A}_{3,3} = 0.1$–0.2	2
$\bar{A}_{3,3} \geqslant 0.5$	3
Average neotectonic rate of displacement (mm/year)	
0–0.05	1
0.06–0.1	2
0.11–0.15	3
0.16–0.2	4
0.3–0.5	5
0.6–2	8
Average quaternary rate of displacemente (mm/year)	
0.1	1
0.2	2
0.3	3
0.4	4
0.5	5
0.6	6
0.7	7
0.8 and more	8

the extent and kinematics of faults and between the width, vertical separation and horizontal throw. On the basis of these ratios, a presumable width of the hidden fault zone is reported in table II.

4˙2. *Stress tensor orientation and horizontal movement of the Earth's crust.* – The study of neotectonic stress conditions implies to establish the kinematics of different scale deformation structures on the basis of structural analysis. The character of the horizontal movements and stress conditions of the Earth's crust in the territory of Georgia has been investigated by means of detailed and regional structural analyses. Figure 6 shows the active faults and their kinematics, revealed with the help of regional structural analysis. Besides, in the same map we report the orientations of the subhorizontal maximum compressive stress axis given by regional structural analysis and, in particular, on the basis of kinematics of different surface faults and major folds. In this respect, particular importance has the above-mentioned study of interferential (transformed) folds. On the map the orientations of the subhorizontal compressive stress axis of the second order are also plotted. They were ascertained by revealing the kinematics of small-scale faults, the jointing analysis, and minor folding. Besides, presumable directions of the Earth's crust motion during the neotectonic stage proceeding from the regional structural analysis are also shown. The directions of the crust motion are in the first place determined on the basis of the folding character, in

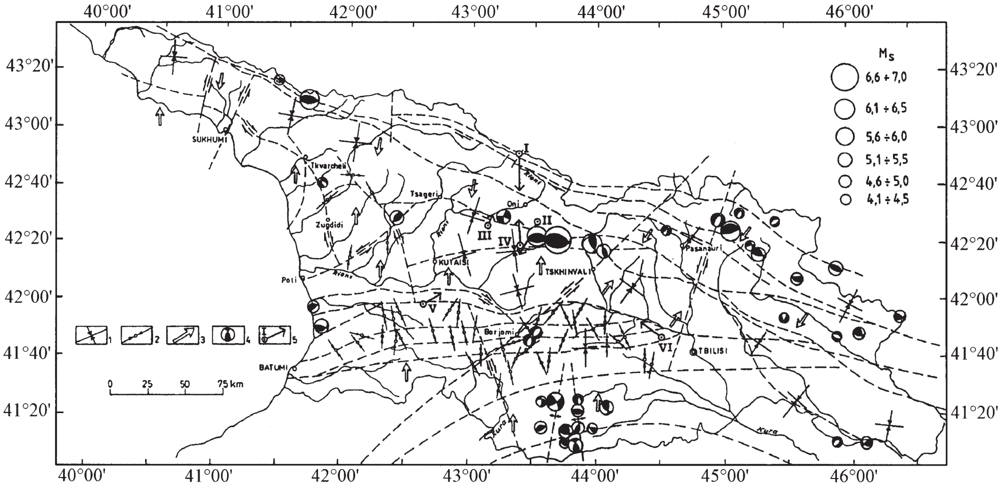

Fig. 6. – Stress tensor orientation map of the territory of Georgia (author: I. Gamkrelidze). The active faults and their kinematics are the same as in fig. 3. 1-2 orientations of the subhorizontal maximum compressive stress axis: 1 of the first order, 2 of the second order (for the western part of the Dzirula terrane we used data of M. Philip *et al.*, [14]; 3 presumable direction of the Earth's crust motion on the neotectonic stage; 4 fault-plane solutions of earthquakes with different magnitudes (which are also shown in the figure); 5 directions of the present motion of the Earth's crust, obtained by means of GPS technology (Prilepin *et al.*, [18]). Points of measurement: I: Khuruti, II: Lesora, III: Khotevi, IV: Sachkhere, V: Vani, VI: Nichbisi.

particular, in the western part of the region, by the existence of the so-called transform folds which show the northward motion of the Transcaucasian (Dzirula) block and the absence of such folds in the eastern part of the Caucasus (to the east of the Tskinvali-Kazbegi fault), where the motion is directed to the NE. This is confirmed by the high rate of late Pleistocene uplift of the eastern part of the Greater Caucasus, which is twice as much as that observed in its western part. Besides, the northward motion of the Transcaucasian block and its subduction under the Greater Caucasus (continental subduction) indicate the analysis of the nappe structures of the southern slope of the Greater Caucasus [12]. However, these directions of the crust motion are "presumable" as they were revealed by indirect measurements, though not numerous GPS data corroborate such character of crust motion including continental subduction.

A special interest arose for the recent deformation of the Earth's crust, as testified by the present seismic activity of the region. The seismicity was taken from the newest Catalogue of Caucasian Earthquakes, lately processed and specified by Georgian seismologists. In particular, we associated the seismic activity to the faults just on the basis of specific and careful earthquake-hypocenter determinations. Naturally we connected the hypocenters with faults taking into account the position of the fault planes.

The recent kinematics of active faults, obtained from earthquake fault-plane solutions (fig. 6), is similar on the whole to the picture of paleokinematics obtained for the neotectonic stage. But, in the areas which are situated between major faults, more complicated stress fields are measured.

Among present-day active faults, it should be mentioned the Tskhinvali-Kazbegi left-lateral strike-slip fault (see fig. 4 and table II) that was established on the basis of geologic, seismic, and earthquake focal mechanisms data [7]. The average neotectonic and quaternary rates of displacement are calculated from the neotectonic and Quaternary vertical separation, horizontal throw of faults, and the time of their activity. The fault's "degree of trustworthiness" was determined by the number of different geological and geophysical signs of fault existence. The more such signs are present, the higher the degree of their trustworthiness is. Whereas the "degree of importance for seismic hazard assessment" was determined by summarizing such important fault parameters as the average rates of neotectonic and quaternary displacement and level of seismic activity, that were obtained on the basis of as more as possible objective data. In table II, the data related only to the Tskhinvali-Kazbegi strike-slip fault were obtained in 1977 by P. D. Gamkrelidze and I. P. Gamkrelidze [7], and those concerning the western part of the Dzirula terrane were obtained in 1989 by Philip *et al.* [14]. On the contrary, all the other data used in fig. 6 are new and original. They were obtained by one author (I. P. Gamkrelidze) on the basis of specific investigations on the territory of Georgia carried out on the occasion of this work. Seismic and focal mechanism data concerning the Tskhinvali-Kazbegi fault [7] indicate that the tectonic motion of the plate situated to the east of this fault is more important than that to the western one. It moves actively to the north and continues underthrusting under the fold system of the Greater Caucasus. This continental subduction takes place in the eastern part of the northern Caucasus and to the north of the Caspian sea seismic zone, dipping to the north [15, 16]. Data used to determine the direction of the crust motion have been mentioned above. But the change of this direction to NE is also supported by the determination of earthquake focal mechanisms (fig. 6). By the way, Philip *et al.* [14] came to the same conclusion.

The processes of the recent northward movement of the Transcaucasian-Caspian plate and the continuous compression of the eastern part of the Greater Caucasus are also emphasized by the high rate of late Pleistocene uplift, which is twice as much as that observed in the western part of the Greater Caucasus [17], and by the present rate of this uplift as well (see below). But, to a certain extent, these data are indirect. Therefore the results of direct measurements of the up-to-date displacement of the Earth's crust by means of GPS technology are of some interest [18, 19]. For this purpose, a regional GPS network in the Caucasus and a local GPS network in the Racha earthquake area, which consisted of 5 points (fig. 6), were realized. Data of direct measurements confirmed the supposed directions of the horizontal movement of the Earth's crust occurred during the neotectonic stage. Direct measurements give naturally a more detailed and precise picture of the movement. In particular, the southernmost points within Georgia—Vani and Nichbisi (points 5 and 6 in fig. 6)—are moving to the NW and NE, respectively, at a relatively low velocity (4.5 ± 0.9 mm/year and 4.6 ± 0.9 mm/year, respectively). The meridional direction of movement under the influence of the Arabian plate, that is characteristic of point Garni situated to the south (outside the country), is distorted within the Adjara-Trialeti fold zone because of the irregular horizontal compression. To the north, in the Racha earthquake area, are situated the GSP points of the local network. Here, Khotevi and Sachkhere (points 3 and 4 in fig. 6) are moving accordingly to the NE and N with the rate 2.9 ± 2.1 mm/year and 4.2 ± 0.9 mm/year, respectively. On the contrary, Khuruti and Lesora (points 1 and 2 in fig. 6) are moving to the S and SW with the rate 6.9 ± 1.1 mm/year and 6.8 ± 1.2 mm/year, respectively. Therefore, it is obvious that the Georgian Block (Dzirula terrane) is moving to the north, whereas the northward of Gagra-Java fault movement (within the fold system of the Greater Caucasus) changes in the opposite

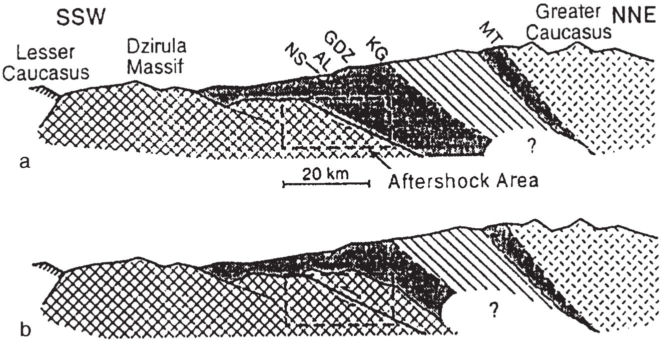

Fig. 7. – Two possible interpretations of the main faults of the Southern Slope of the Greater Caucasus (after Triep *et al.*, [20]. a) Fault thrusts sediment over the basement. b) Faults lies within a shallow basement. 1 Cretaceous, 2 Jurassic, 3 pre-Jurassic basement of the Main Range zone of the Greater Caucasus; 4 pre-Jurassic basement of the Dzirula massif. Abbreviations are AL, Abkhaz-Lechkhumi (Gagra-Java) fault; GDZ, Gagra-Java zone; KG, Krasnopoliansk-Gazduchay overthrust; MT, Main overthrust and NS, Neogene sediments.

direction. This corroborates the opinion of continuing underthrusting of the Transcaucasian plate under the Greater Caucasus [7, 8, 12]. It is interesting to note that Triep *et al.* [20] also came to the same conclusion, on the basis of the spatial location of aftershock epicentres and hypocentres, and of focal mechanisms of the mainshock and four larger aftershocks of the Racha earthquake. They gave two possible interpretations of the main underthrust fault as shown in fig. 7.

All the above-mentioned data suggest a slightly new interpretation of the recent continental subduction zone along the southern slope of the Greater Caucasus (fig. 8). Apparently, the pre-Jurassic crystalline basement undergoes the main underthrusting. Nevertheless, the sedimentary cover is also involved in the underthrusting process and undergoes underthrusting along the Gagra-Java fault, that was testified by GSP data. Comparatively, the fast northward motion of the Georgian Block, that is conditioned by Tskhinvali-Kazbegi left-lateral fault, causes not only the underthrusting of the Georgian Block, but also that of the Gagra-Java zone (subterrane), that is completely

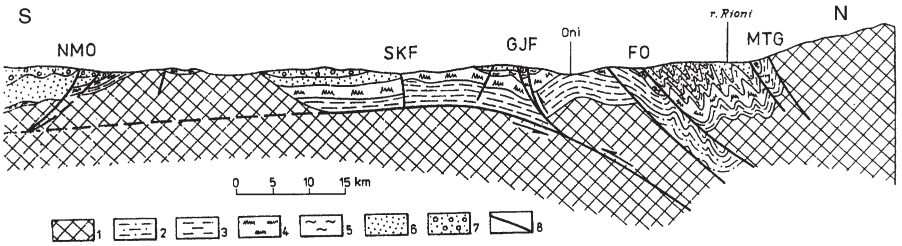

Fig. 8. – Map of the present continental subduction zone of the southern slope of the Greater Caucasus (author: I. Gamkrelidze). 1 pre-Jurassic cristalline basement, 2 Middle-Upper Paleozoic, 3 Lower Jurassic, 4 Middle Jurassic, 5 Upper Jurassic, 6 Cretaceous, 7 Paleogene and Neogene, 8 faults. NMO, Northern marginal overthrust of Adjara-Trialeti, SKF, Sachkhere-Kutaisi fault, GJF, Gagra-Java fault, FO, Frontal overthrust of the Greater Caucasus nappes, MTG, Main thrust of the Greater Caucasus.

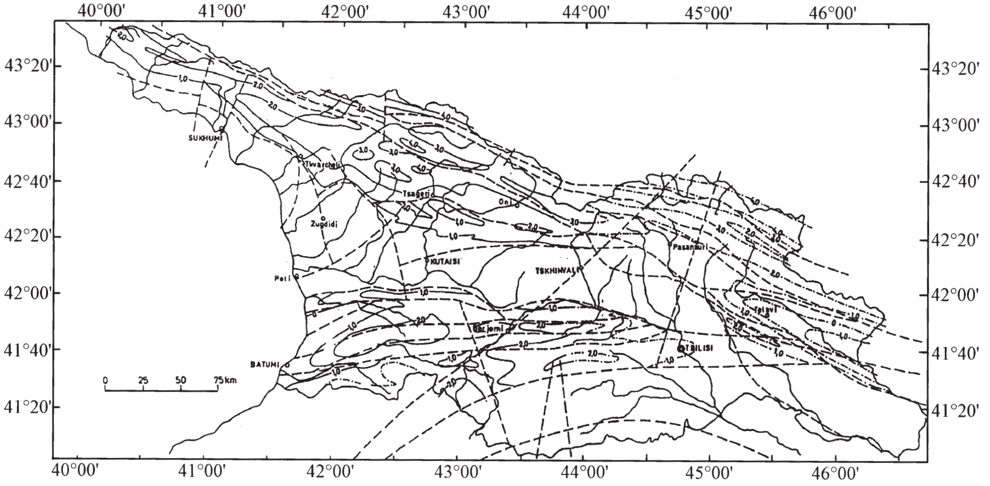

Fig. 9. – Deformation of the upper Pliocene planation surface of Georgia (author: S. Kuloshvili). Erosion surfaces are developed within the Greater Caucasus and the Adjara-Trialeti zone.

overlapped by nappes of flysch zone. Here, within the Kura depression, the molassic cover is detached from older sediments and shifted to the south along with the nappes of the Greater Caucasus [7]. Then, it is natural to share Philip *et al.*'s [14] opinion about the existence of a more "mature" stage of continental collision in the eastern Caucasus than in the western one.

4·3. *Vertical movement of the Earth's crust.* – Vertical movements can be studied by means of different structural-geomorphic methods. Here we report the results obtained on the basis of planation surface analysis. Erosion surfaces are developed within the Greater Caucasus and the Adjara-Trialeti zone, where the united planation surface reconstructed by many researchers is dated as upper Pliocene. The map of deformation of this surface (fig. 9) exhibits the total amplitude of the vertical movements which occurred since the end of the Akchagil (for the last 2 Ma). The map is constructed on the basis of the present position of the upper Pliocene (post-Akchagil) planation surface. Since the formation of the surfaces (abrasion surfaces, accumulative plains and others) took place at the low altitudes, their present position approximately corresponds to the vertical amplitude of the newest movements.

The analysis of the planation surface deformation character exhibits the arch-block nature of the newest uplift of the Greater Caucasus, which is less manifested in the Adjara-Trialeti zone.

The deformation since Upper Sarmatian (fig. 10) is constructed on the basis of actual data only in the depression area. In spite of the elevation area, the corresponding surfaces are almost not preserved in relief and have to be reconstructed by means of different methods: graphic method of completion of geological profile, calculation of denuded material volume, thickness of denudation cut, etc.

The study of molassic formation of the Mio-Pliocene age shows that it consists almost completely of Upper Jurassic and Cretaceous flysch limestones. This fact indicates that, as far back as in early Pliocene-Upper Mesozoic, the sedimentary cover had spread within the whole Greater Caucasus. Because here, at present, crop out

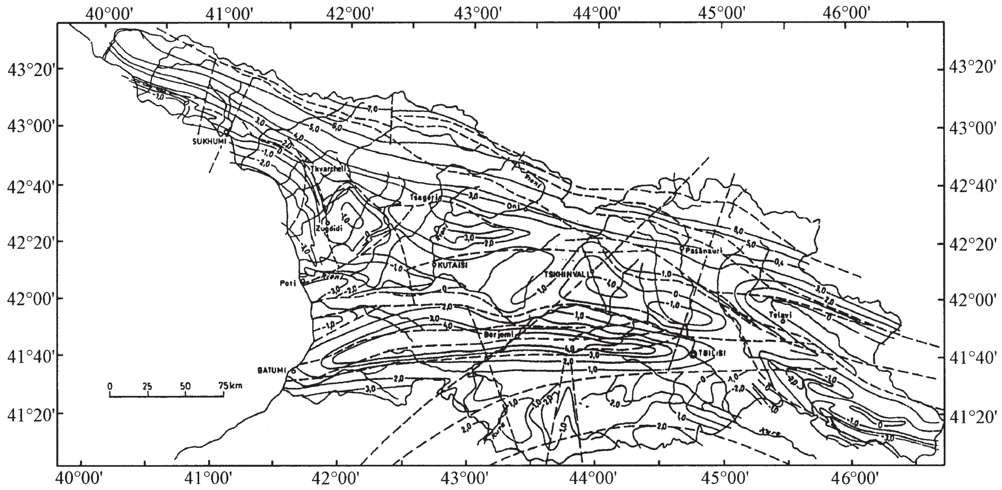

Fig. 10. – Total deformation of the territory of Georgia for the neotectonic stage, since upper Sarmation (author: S. Kuloshvili).

Lower Jurassic and Paleozoic deposits, the thickness of denuded layer must equal roughly 3-4 km in the axial part of the Greater Caucasus decreasing to its peripheries.

The vertical movements for the postakchagil-Quaternary period pointed out not high average rates when compared with the corresponding ones of the Quaternary (table II). They were found to be between a fraction of mm/year and 1-2 mm/year for the axial part of the fold zones and along the faults, respectively. Higher rates (3-15 mm/year) of present vertical movements were obtained according to the data of repeated leveling, as well as for the last 10-20 thousand years by terrane analysis [21]. Lilienberg and Shirinov [22] obtained rates of 2 mm/year for the uplifting of the western part of the Greater Caucasus, ~ 10-13 mm/year in the axial zone of its central part, and over 15 mm/year in its eastern part. The gradients of the present movement along the main thrust of the Greater Caucasus reach 1.5 mm/year by 1 km. The transversal Dzirula uplift rises with a rate of 3-5 mm/year. The Tskhinvali-Kazbegi left-lateral fault is characterized by gradients of movement of 0.1-0.5 mm/year by 1 km. The axial part of the Adjara-Trialeti fold zone undergoes uplifting with a rate of 2-3 mm/year. The rates of sinking are (2-4) mm/year in the central part of Rioni depression (in the neighbourhood of Poti 6.5 mm/year), in its northern part (1-3) mm/year, and in Kura depression 1.5 mm/year. The superimposed Alasani depression undergoes relative sinking against the background of general uplifting of the region, which is of 6-8 mm/year [22].

4·4. *Seismicity.* – Figure 11 shows the active faults and epicentres of earthquakes with $M \geqslant 3.5$ occurred in the Caucasus of Georgia during the last century. Some historical events are also reported in the same figure.

The seismicity shows a non-uniform spatial distribution: earthquakes are mainly concentrated in the southern Mskheti-Akhalkalaki region and along the north-eastern part of the Caucasus chain bordering on the north-eastern Republic of Georgia.

Discrete structures of crustal interest (crustal blocks) bounded by active faults are also shown. They are common in seismic areas. Another example of such structures has

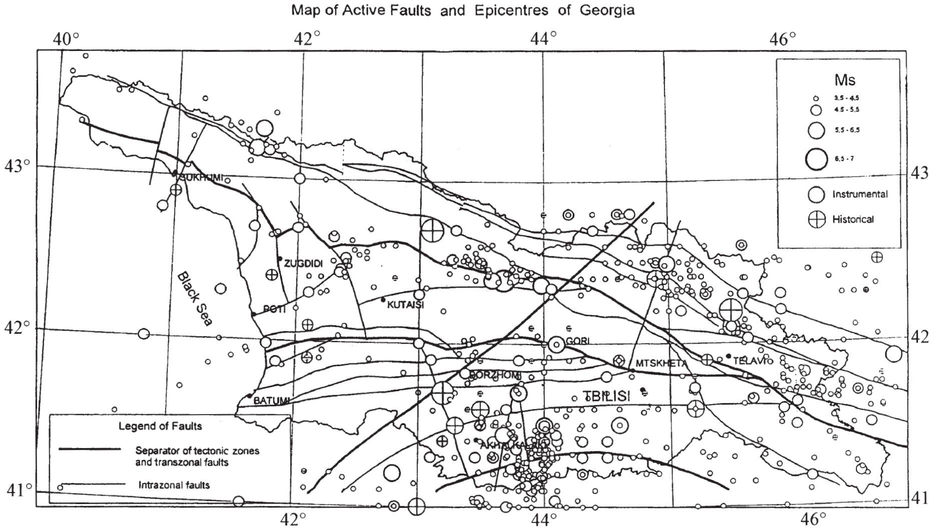

Fig. 11. – Seismotectonic map of the Caucasus. The figure reports active faults and epicentres of earthquakes with $M \geqslant 3.5$ occurred in the Georgian region during the last century. Some historical events are also reported.

recently been pointed out in the Latium-Abruzzi carbonatic platform belonging to the central Apennines in Italy [23, 24], where investigations similar to those reported here are carried out jointly by Georgian and Italian geophysicists.

4·5. *Ground tilt monitoring.* – Residual daily averaged ground tilt data, obtained in the period 1990-1991, from the Varzia tilt site (VAR) located in the Mskheti-Akhalkalaki seismic region of the southern Caucasus, are shown in fig. 12. The

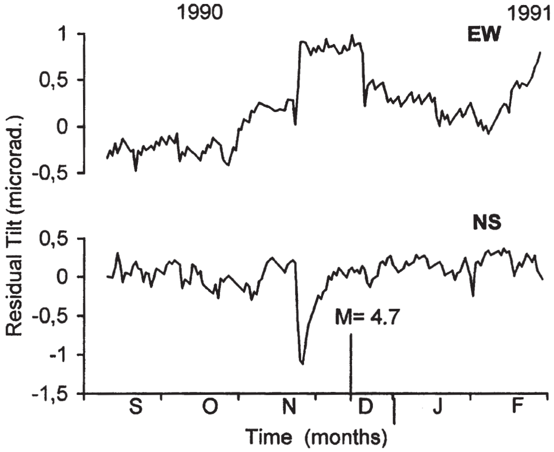

Fig. 12. – Residual ground tilts obtained in Georgia in the period 1990-1991 by removing the secular tectonic trend and seasonal cyclic variations from the VAR daily averaged tilt component data.

general character of the raw tilt variations were found to be similar to that observed in other seismic areas like the central Apennines in Italy [5]. In both cases data showed seasonal and long (or secular)-term systematic tilts on which shorter-term perturbations were superimposed with time spans of weeks to some months. Shorter-term tilt changes with duration of days, but of very low amplitude, were also observed.

The secular and seasonal tilt trends demonstrated to be an increasing monotonic function of tectonic origin and periodic oscillations of thermoelastic origin, respectively [5]. They were removed from the raw data, since we are interested in ground motions that occur on a local scale.

On the contrary, the intermediate-term tilt variations of fig. 12 can be associated to a different class of deformations that are non-monotonic functions of time [25, 26]. They are anomalous both in amplitude (being over the 3σ level of the tilt background) and in frequency, showing oscillations with a duration of months (that is, remote from the high-frequency content associated with tides, daily thermoelastic effects and instrumental noises as well as from the low-frequency phenomena connected with seasonal thermoelastic effects and secular variations).

To investigate the possibility that these characteristics intermediate-term tilts be of preseismic origin, the strongest earthquakes that occurred in the Mskheti-Akhalkalaki region were considered and both tiltmeter-earthquake distance R and magnitude M were taken into account. Two earthquake selection criteria based on the ε strain parameter introduced by Dobrovolsky *et al.* [27] and the R/L ratio (L being the source dimension) were used [28-30]. On the basis of previous studies [28, 31], favorable results were obtained when $\varepsilon \geqslant 10^{-8}$ and $R/L \leqslant 10$. Only one seismic event exceeded these threshold values during the tilt measurement period. It was the Javakheti earthquake of December 16, 1990 ($M = 4.7$) which occurred 49 km E of the VAR site and gave $\varepsilon = 6.3 \times 10^{-8}$; $R/L = 5.5$. It is reported in fig. 12 with a vertical bar. As can be seen in the figure, the onset times of both the two tilt anomalies (*i.e.*, anomalous variations observed in both the two tilt components), precede the time of occurrence of the Javakheti seismic event. Therefore, these intermediate-term tilt anomalies can be tentatively considered as possible earthquake precursors.

Figure 13 shows the best fitting of the EW tilt anomaly reported in fig. 12, carried

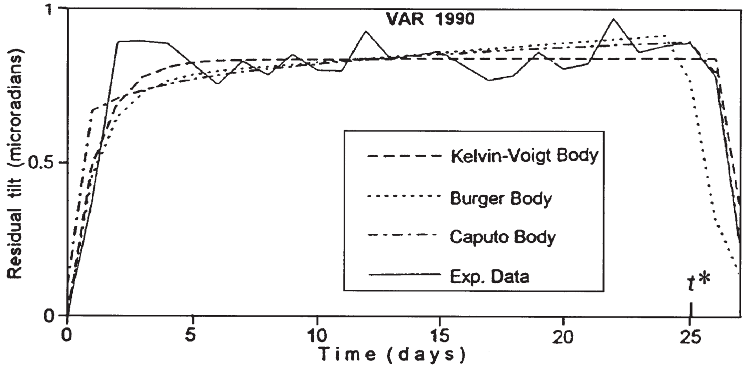

Fig. 13. – Data fitting of the EW residual tilt of fig. 12 with creep curves from Kelvin-Voigt, Burgers, and Caputo viscoelastic models.

out with creep functions from the linear Kelvin-Voigt, Burgers, and Caputo viscoelastic models.

Also in this case, results of similar quality were obtained in the central Apennines in Italy where one also pointed out their slow-propagating character (0.1–10 cm/s) observed up to some tens of kilometers from the earthquakes of magnitude 4.0 or less [32]. These creep-related tilt precursors were modeled [26, 33] under the hypothesis that the local tectonic stress field relaxes through the crustal blocks of the region, giving rise to a propagating effect at a distance, regulated by the rheological properties of the fault materials which separate the oscillating blocks mentioned in subsect. 4·4.

In this way, the stress and strain fields generated in the preparation focal area can reach distances that are greater than those estimated by quasi-static models [34]. This could apply to the experimental intermediate-term oscillations reported here.

To facilitate the understanding of the mechanisms that determine the characteristic tilt response to the observed seismicity, it is of fundamental importance to study the dynamic behavior of the crustal blocks system belonging to each investigated seismic area. Particularly, the exact geometry and dimension of the blocks as well as their relative motions and the contributions of the fault materials remain to be determined. This, in order to thoroughly study the local stress and strain fields, as well as their propagation suggested by previous theoretical and experimental results [24, 26, 32, 33, 35-37]. For this purpose, tiltmeters located at different crustal blocks of the regions under study as well as strainmeter arrays along the same discrete structures are required, in order to evaluate both rotation and strain tensors fields.

At present, experimental data [5, 32] seem to confirm that the tectonic stress concentration in the preparation focal area of an earthquake can be considered as a possible mechanism for the tilt and strain precursor generation.

The aseismic creep episodes that occur in the fault materials and beneath blocks are instrumental in transferring and concentrating stress in other zones of the region, thus, in producing the conditions which can favor other earthquakes. As some authors speculated [24, 26, 33, 37], the migration of a deformation front might trigger other earthquakes, if it impacts areas of high seismic potential. In this sense, studies of migration effects can contribute significantly to earthquake prediction studies.

The viscoelastic properties of weak transition zones, where aseismic creep episodes occur, can be justified by the fact that these zones are strongly cracked so that their moduli of rigidity can be considered as less than those of the adjacent crustal blocks, and their behavior can be studied with the introduction of a viscous parameter [38, 39]. The viscous component of the transition zones may be due either to the existence of a fault gouge and of infiltrated fluid, or to temperature and pressure effects that, like the rigidity, depend on the depth [40, 41].

5. – Conclusions

The neotectonics of the Caucasus was connected with the active northward movement of the Arabian plate that wedged between the Anatolian and Iranian plates and moved them apart causing the origination of specific structures of deformed folds, longitudinal squeezing and shear structures (strike-slip faults).

In the shortened sector of the Caucasus a whole system of deep faults arose (showing different direction and order), which continue to develop at present and are the principal seismogenetic structures.

Detailed studies of deep fault systems on the territory of Georgia, as a test area for seismic hazard assessment in the Caucasus, gave us the opportunity to compile the map of active faults and their catalogue.

Important parameters of the active faults of Georgia allow to define numerical expression of trustworthiness and importance for seismic hazard assessment.

The orientation of the maximum compressive stress axis of the first and second order, obtained by means of regional and detailed structural analyses, shows on the whole submeridional compression of the region, but also a change in the direction of this compression to the north-east, in the plate situated to the east of the Tskhinvali-Kazbegi left-lateral fault.

The recent kinematics of active faults, from earthquake fault-plane solutions, is similar to the paleokinematics one, obtained for the neotectonic stage. The data obtained on the basis of direct measurements of the Earth's crust displacement (GPS technology) confirm on the whole the directions revealed by means of other methods. The same data also corroborate the existence of the present underthrust zone (continental subduction) along the southern slope of the Greater Caucasus, where the pre-Jurassic crystalline basement undergoes the main underthrusting. The neotectonic vertical movements, revealed on the basis of planation surface analysis, envelope mainly the Greater Caucasus and Adjara-Trialeti fold zone. Relatively small average rates of vertical movements for the neotectonic stage on the whole and for postakchagil-Quaternary period were observed. But the rates of the present vertical movements are significantly higher.

Results from the VAR tilt site of the Mskheti-Akhalkalaki region, obtained in the occasion of the Paravani earthquake, indicate that the intermediate-term precursory tilts can be tentatively considered as possible earthquake precursors.

The theoretical tilt curves fit well such tilt fluctuations, indicating that they can be the manifestation of aseismic creep strains in the viscoelastic fault materials caused by the fault slip close to the tilt site. Slippage is probably due to the slow propagation of a stress-strain field through the crustal blocks of the region with source in the preparation focal area.

More in general, it is of particular interest to identify different seismic regions having similar behavior. Some of such similarities between Caucasus and Central Apennines (crustal blocks with similar geometry and geodynamics, and fault creep-related tilt precursors within the framework of similar rheology) have been mentioned in sect. **1**, and subsect. 4˙4 and 4˙5. As concerns seismicity, some differences have been observed in the earthquake magnitude (greater in the Caucasus) and in the focal mechanism which is mainly compressional in the Caucasus (fig. 6), and prevailing extensional in the Apennines [42].

* * *

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