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Analysis of global gravitational precursors before some Asian strong earthquakes

E. Khalilov[1]***, L. Wang***[2]***, L. Khalilova***[3]***, 2019***

[1]Global Network for the Forecasting of Earthquakes, Baku, Azerbaijan
[2]Lanzhou Institute of Seismology, China Earthquake Administration, Lanzhou, China
[3]Azerbaijan State Oil and Industry University, Baku, Azerbaijan
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Розглянуто гравітаційні попередники мегаземлетрусів в Азії та Південно-Східній Азії: Сичуань, M7.9, 12 травня 2008 р.; Андаманські острови, M7.5, 10 серпня 2009 р.; острови Самоа, M8.1, 29 вересня 2009 р.; Північна Суматра, M7.8, 06 квітня 2010 р.; Тохоку, M9, 11 березня 2011 р. Усі гравітаційні попередники були записані з використанням станцій прогнозування землетрусів ATROPATENA. Запропоновано створення міжнародної системи прогнозування землетрусів на отриманих результатів. Для моніторингу просторово-часових варіацій гравітаційного поля розроблено та виготовлено спеціальні детектори — станці ATROPATENA. Детектори безперервно вимірюють величину гравітаційної сталої *G* у взаємно перпендикулярних напрямках і відносні значення сили тяжіння Δg. До і після мегаземлетрусів в Азії та Південно-Східній Азії виявлено зміни гравітаційного поля Землі на великих відстанях від епіцентру (близько 8000 км); їх виміряли станції ATROPATENA у Баку (Азербайджан) та Джокьякарта (Індонезія). На показники балансу Кавендиша при вимірюванні гравітаційної сталої *G* впливають просторово-часові зміни зовнішніх гравітаційних полів геологічного походження, які з часом змінюють ознаки справжніх значень *G*. Вимірювання справжнього значення гравітаційної сталої *G* на поверхні Землі з точністю, що перевищує другу цифру після десяткової крапки, неможливе через просторово-часові варіації гравітаційного поля під впливом геодинамічних процесів.

Уперше ідентифіковано справжню причину коливань записаних значень гравітаційної сталої *G*. Ці варіації були предметом наукових дискусій протягом усього минулого століття.

Ключові слова: прогнозування землетрусів, гравітаційні попередники, тектонічні хвилі, станція ATROPATENA, сейсмологія, геодинаміка, геотектоніка.

Introduction. During the whole history of humanity the people have been trying to learn the possible natural cataclysms beforehand. It is mentioned in ancient historical sources, legends, myths and in religious writings. For this purpose they used all accessible for them opportunities in accordance with their level of knowledge and philosophy. They tried to use astronomical phenomena and they associated the natural cataclysms with them. For example, ancient people take the solar eclipses, approaches of the Mars to the Earth, appearance of spots on the Sun, unusual behavior of animals and unusual phenomena in atmosphere as special signs of approaching of the catastrophe.

How far have the modern scientists gone from their predecessors? If we try to make parallels, we'll see that the modern science with more interest studies the influence of planets of solar system, solar activity and other cosmic factors on seismicity and volcanism. Meanwhile, for short-term forecasting the earthquakes different precursors of earthquakes are also used (as earlier). The main difference is in explanations of the mechanism of connection between the observed precursors and the process of preparation of the earthquake. Another main difference is the application of modern recording equipment, which use high tech. In other respects «philosophy» of forecasting the earthquakes practically hasn't been changed.

Short-term forecasting of earthquakes: pros and cons. The scientific researches, aimed at creation of effective technology of forecasting the earthquakes were financed about 100 years in many developed countries of the world. Disappointment of public officers and wide mass of the population because of absence of serious achievements in this sphere can be understood. Seismologists, who forecast the earthquakes and spent milliards of dollars in the whole world, found themselves in difficult and delicate situation. Most of them were looking for justifications of their scientific failures, and gladly found them during international scientific meeting which was called in London on 7—8 November 1996 on the subject of interrelation of earthquakes with other phenomena in order to forecast them. Transactions of this meeting were published in [Geller, 1997].

During this authoritative forum the famous seismologist Dr. Robert J. Geller declared the impossibility in principle of forecasting the earthquakes. His main idea is that the process of preparation of the earthquake source has a big probability of randomness and influence of many external factors. That is why he considers this process as a maximally approximate to chaotic processes. Many further articles and speeches of Dr. Robert Geller were the continuation of his idea about impossibility of forecasting the earthquakes. This idea is reflected in his basic statement: «Research in the sphere of forecasting the earthquakes have been carrying out more than 100 years without evident success. The results of researches didn't allow receiving the great achievements. The extensive researching was not able to find reliable precursors. Our theoretic work supposes that break displacement is nonlinear process, which is very sensitive to unknown details of structure of the Earth in bulk, and not only in immediate proximity to the epicenter. «The reliable accordance of alarms about unavoidable strong earthquakes is inefficient and impossible» [Geller et al., 1997].

Registration of different precursors in big distances from epicenters

Now there is known more than 300 precursors of earthquakes of different character and origin. During the last years a number of scientists published the results of researches, indicative of possibility of registration of strong earthquakes precursors in the distance of more than 5000 km, and in some cases more than 10 000 km [Petrova et al., 2005; Hasanov, Keramova, 2006; Khain, Khalilov, 2006; Kopilova et al., 2007; Lyubushin, 2008; Sobolev et al., 2008; Khalilov et al., 2011].

Seismic-gravitational precursors. So, as a result of researches, carried out by the department of physics of the Earth of Petersburg's State University, seismic-gravimetric complex in Petersburg has registered the long-term tensile deformation (vertically) with duration of 12 days and nights, which forestalled the cycle of strong earthquakes of December 2004, including the strongest earthquake on the north of Sumatra island on 26.01.2004, which caused the catastrophic tsunami. Before each strong earthquake there were registered the deformations of less continuation (1—2 days and nights), which were observed earlier too. There was also noted the increasing of intensity of seismic-gravitational fluctuations, which accompany these deformations, the beginning of which always advanced the moment of breaks of strong earthquakes for 1— days and nights. At that, the first estimates of speed and length of waves: low-speed waves (speed from 0,35 to 0,68 km/s) of seismic origin had long from 1520 to 7310 km. As a result of analysis of the received data the scientists came to the conclusion that the observed fluctuations are connected with the deformational processes, which are taking place inside the continent with the complex block-hierarchical structure [Kopilova et al., 2007].

Tideless variations of gravity. So, from 2002 the Scientific-Research Institute of forecasting and studying the earthquakes (Baku) has been carried out the continuous measurement of tideless variations of gravity in the station «Binagadi», which is located in

Absheron peninsula 24 km from Baku. The measurements were carried out simultaneously by four high-precision quartz gravimeters of KV and KS types. As a result of measurements and interpretation of the received data, there were found out the gravitational signals in variations of gravity, which preceded the strong earthquakes, the epicenters of which are in big distances (in the radius of two thousand to ten thousands km) from the registered stations. In the process of interpretations of results of researches there were deducted the gravitational effects from lunar and solar tides. As it is known, the solar tides cause the variations of gravity which do not exceed 0,1 mGal, and the amplitude of lunar variations is about 0,2 mGal. Changes of tideless variations of gravity were registered before strong earthquakes in Indonesia, Pakistan, Japan, Taiwan, India, the Philippines and Iran.

Statistic data show that the gravitational signals were registered more than in 85 % cases, on the average, 5—10 days before strong earthquakes [Khain, Khalilov, 2006].

Classification of the considered «long-range»precursors. So, the carried out brief review allowed marking out a few precursors of earthquakes, which appear in big distances between registering points and epicenters of earthquakes:

- seismic-gravitational anomalies [Petrova et al., 2005];
- tideless variations of gravity [Khain, Khalilov, 2006];
- changes of hydro-geo-chemical mode [Hasanov, Keramova, 2006];
- changes of the level of ground waters [Ludwin, 2001];
- synchronization of micro-seismic noise [Lyubushin, 2008; Sobolev et al., 2008];
- long-period three-dimensional variations of gravitational field [Khalilov et al., 2011].

We didn't review some other precursors, which also display in big remoteness from epicenters of strong earthquakes (variations of different parameters of ionosphere, electromagnetic noise disturbances, electric, magnetic and other precursors).

Methodology. A new instrument for experimental study of the space-time variations of measured values of G was created, called the ATROPATENA detector [Khalilov, 2013].

ATROPATENA is a system of sensors closed and isolated from the environment, using the physical principle of the Cavendish balance, with small weights on the ends of two (instead of one) mutually perpendicular balance-beams hung by threads *2*. Between the small weights and large weights are placed equally spaced 3, Fig. 1, *a*.

The third measuring sensor, the trial mass *4*, is hung on a special elastic lever and makes available the possibility of vertical displacements during changes in the relative values of acceleration of gravity, Δg. Variations of Δg are stipulated for luni-solar floods and for the appearance of local gravitational anomalies, which can be caused by the changing of density of rock mass under the instrument as a result of changes in their stress condition, and consequently their mass. As seen in the scheme, on the balance-beams with the weights *2* and on the lever of the vertical sensor *4*, there are tiny mirrors on which three laser beams are directed. Being reflected from the mirrors, the beams hit the sensitive optical matrix *6* and *7*, where the transformation of optical signal from laser mark into electric signals and their transmission into an analog-to-digital converter occurs. After that, the digital signal is transmitted to a special block of the computer as the next record in a special format. The software, written at the Scientific-Research Institute of Forecasting and Studying of Earthquakes (SRIFSE), automatically records the information in the form of separate files for a period of time determined by the operator.

The entire sensitive system is placed into the special, isolated from the environment, glass body *1*, where a deep vacuum has been created and is constantly supported (10^{-4} MPa). Temperature sensors accurate to 0,1 °C are placed in different sections of the sensitive system and connected to the temperature control block. For excluding the mechanical effects and for better heat insulation, the vacuum body with the sensitive system is placed into translucent plastic body which

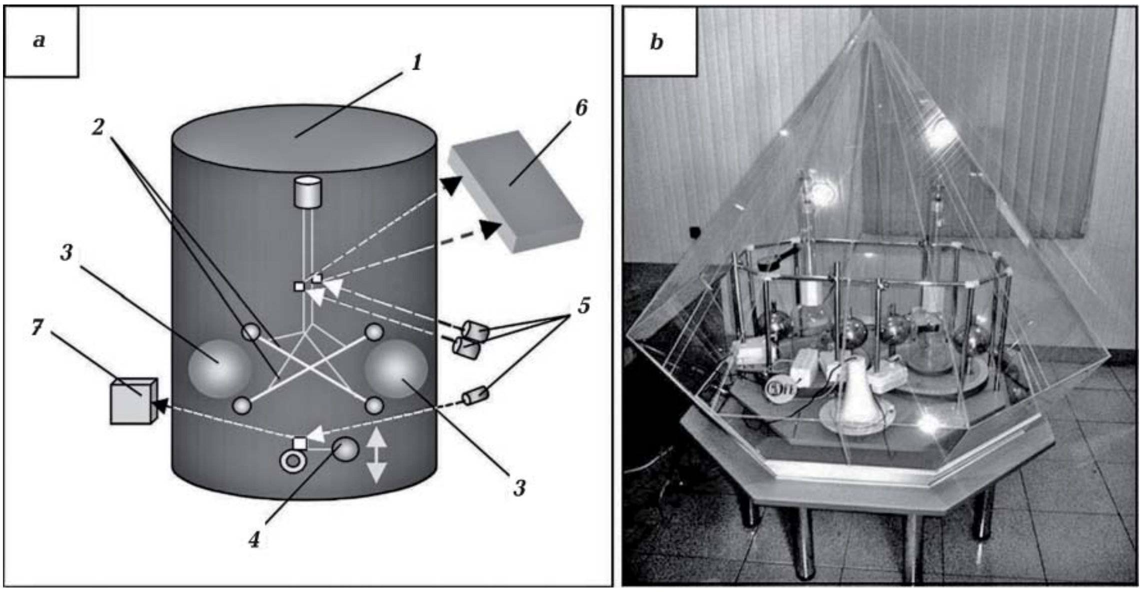

Fig. 1. The ATROPATENA station is shown schematically (*a*); photo of ATROPATENA CRYSTAL Kh11 Station in Baku (Azerbaijan) (*b*): *1* — glass body of the detector; *2* — balance-beams with small weights on the ends; *3* — big weights; *4* — trial weight hung on elastic lever; *5* — laser emitters; *6* — sensitive optical matrix for horizontal sensors; *7* — sensitive optical matrix for vertical sensor.

also allows to observe the work of the system visually Fig. 1, *b*.

Together with the noted sensors, ATROPATENA is also provided with a digital seismic station using a three-component seismic receiver, the information of which is also transmitted to the computer and is continuously recorded in three channels X, Y, and Z digitally.

The registration of seismic fluctuations is necessary in order to exclude the possible influence of these fluctuations on destabilization of the sensitive system of the ATROPATENA detector and the appearance of false anomalies caused by seismic processes. The remote control of the detector and remote pickup of information minimize the external influences on the sensitive system.

All elements of the sensitive system have been made of non-metallic materials to exclude the influence of magnetic fields and electromagnetic radiation on these elements. ATROPATENA stations is placed in: the building of the Scientific Research Institute of Forecasting and Studying of Earthquakes in Baku (Azerbaijan); Building of Governor of Yogyakarta (Indonesia); Center for Earthquakes Study, Islamabad (Pakistan); SETAC Ltd. Istanbul; Institute Geophysics of National Academy of Sciences of Ukraine, Kiev. Since 1 April 2007 the first station ATROPATENA has been in operation, and has recorded high-quality information about variations of the gravitational field over time in three axes X, Y, and Z, and the seismologic information simultaneously recorded by means of the Tethys-SD wide-band digital seismic station. First, ATROPATENA station was provided for experimental research on the possible influence of tectonic waves on indications of the Cavendish balance.

However, this detector does not measure changes in the gravitational constant G but rather deviations of the Cavendish balance's indications, being influenced by altered external masses of geological origin. It should be taken into account that astronomical masses such as luni-solar tides affect indications of the Cavendish balance as well. But this influence is very weak and is reflected in the gravitational constant values in the fifth and sixth digits after the decimal point [Khalilov, 2004].

ATROPATENA station's measuring parameters. The ATROPATENA station measures the ΔG index which is the difference between the gravitational constant G (initially measured G value) and measured values of the Cavendish balance at the measurement time G_F:

$$\Delta G = G - G_F. \quad (1)$$

The ATROPATENA-AZ station (Baku, Azerbaijan) was used to register gravity anomalies before strong earthquakes, namely in Japan on 7 May 2008 and Sichuan, China on 07, 12, 13 and 17 May 2008 and other earthquakes [Khalilov, 2009a,b, 2013; Khalilov et al., 2011]. Since only relative changes of the gravitational field reflecting deviations from the initially measured G value are important for researchers, a conventional index of variations of the gravitational field ΔG was taken as a basis for registration and subsequent analysis. To convert the ΔG index into a gravitational constant G measuring unit, the recorded ΔG index should be accepted at the first approximation as the G value starting from the second digit after the decimal point. According to CODATA (https://www.nist.gov/sites/default/files/documents/pml/div684/fcdc/Motivation.pdf) as of April 2011, the value of the gravitational constant G is $6{,}674\ 28\times10^{-11}$ m^3 $kg^{-1}s^{-2}$, standard uncertainty $0{,}00067\times10^{-11}$ $m^3kg^{-1}s^{-2}$, relative standard *uncertainty* $1{,}0\times10^{-4}$, concise form $6{,}674\ 28(67)\cdot10^{-11}$ $m^3kg^{-1}s^{-2}$. So, only two digits after the decimal point remain unchanged in the measured value of the gravitational constant G; from the third digit on, the ATROPATENA stations register periodical spatio-temporal variations that depend on the location of the recording device and its spatial orientation:

$$G_F = 6{,}67(\pm\Delta G)\cdot10^{-11}\ \mathrm{m^3kgs^{-2}}, \quad (2)$$

where G_F is the actually measured value of the gravitational constant at the measurement time.

Researches have found that ΔG records obtained using the mutually perpendicular Cavendish balance are not always synchronized and often lack a pronounced correlation [Khalilov et al., 2011]. This fact can also be observed from the records of all the stations before and after the disastrous Japanese earthquake of March 11, 2011. Along with measuring AG, the ATROPATENA stations simultaneously register variations in time of relative values of gravity Ag, using a microgravimeter installed inside the vacuum tank. Δg values arc also measured in arbitrary units to facilitate research. If necessary, the measured Ag values can be converted to mGal. Among the participant of the experiments and their analysis were organizations: Global Network for the Forecasting of Earthquakes (GNFE, London, UK, www.seismonet.com), Scientific Research Institute for the Forecasting and Studying of Earthquakes (Baku, Azerbaijan) and Lanzhou Institute of Seismology (Lanzhou, Gansu, China).

Measurement results. From 2008 to 2013 the ATROPATENA earthquake forecasting stations of the Global Network for the Forecasting the Earthquakes (GNFE) recorded the gravitational precursors of earthquakes before all major earthquakes in Europe, Asia and Southeast Asia. Let us consider the most interesting and characteristic records of gravitational precursors of earthquakes and gravitational effects before, during and after strong earthquakes that were registered by ATROPATENA-ID stations (located in Yogyakarta, Indonesia) and ATROPATENA-AZ (located in Baku, Azerbaijan). Hereinafter we will call the records of ATROPATENA stations «the gravitograms».

Let us consider the gravitogram records for the following strong earthquakes: 1) Tohoku, March 11, 2011, M9.0; 2) Sumatra, April 06, M7.8, 2010; 3) Samoa, September 29, 2009, M8.1; 4) Andaman, August 10, 2009, M7.5; 5) Sichuan, May 12, 2008, M7.9.

Analysis of gravitogram of the earthquake Tohoku, March 11, 2011, M9.0. We have considered the recording of gravitogram of the earthquake in Tohoku, March 11, 2011, M9.0 (Fig. 2, *a*, *f*) made by the ATROPATENA-ID station. The distance between the epicenter and the ATROPATENA-ID station was 5,950 km.

Table 1 shows the parameters of a strong earthquake in Tohoku, as well as foreshocks and aftershocks.

Fig. 2 shows maps of the epicentre zones of the earthquakes under consideration (*a*—*e*) and gravitograms of these earthquakes (*f*—*j*).

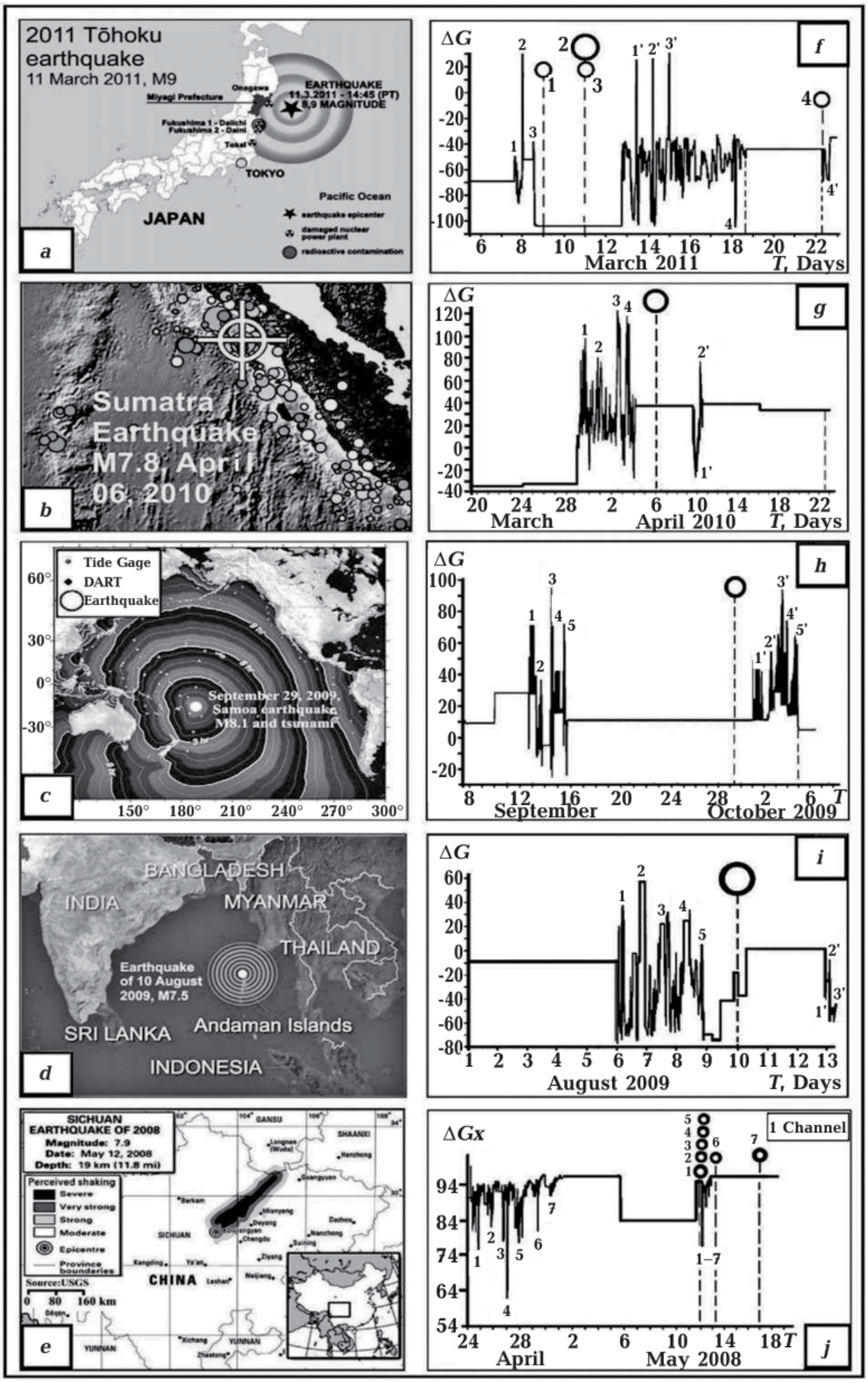

Fig. 2. Maps of the epicentre zone of the earthquakes in: Tohoku, March 11, 2011, M9.0 (*a*); Sumatra, April 06, 2010, M7.8 (*b*); Samoa, September 29, 2009, M8.1 (*c*); Andaman, August 10, 2009, M7.5 (*d*); Sichuan, May 12, 2008, M7.9 (*e*). Recording of gravitogram of ATROPATENA-ID (in Indonesia) station before, during and after earthquakes: Tohoku (*f*); Sumatra (*g*); Samoa (*h*); Andaman (*i*); recording of gravitograms of ATROPATENA-AZ (in Azerbaijan) station before, during and after Sichuan earthquake (*j*). Δ*G* — index which is the difference between the gravitational constant *G* (initially measured *G* value) and measured values of the Cavendish balance. The Δ*G*-index values correspond to the value *G* starting from the third decimal place; *1*, *2*, *3*... — numbers of gravitational precursors; *1′*, *2′*, *3′* — secondary gravitational anomalies. Moments of earthquakes are designated by the circlets.

Table 1. Earthquakes parameters in Japan from 09 to 22 March 2011

No	Date, time (UTC)	Location	Depth, km	Magnitude
1	March 09, 2011 02:45:20	38.440°N, 142.840°E	32	7.3
2	March 11, 2011 05:46:24 UTC	38.297°N, 142.372°E	30	9.0
3	March 11, 2011 06:15:40 UTC	36.281°N, 141.111°E	42	7.9
4	March 22, 2011 07:18:47 UTC	37.249°N, 143.956°E	26.5	6.6

It should be noted that the gravitograms *f*—*i* have been recorded by the ATROPATENA-ID station, and the gravitogram *j* has been recorded by the ATROPATENA-AZ station.

On the gravitogram (Fig. 2, *f*) it is clear that before the indicated series of earthquakes three gravitational anomalies were registered. The first and the second ones on March 7 at 17:15 and at 21:57; the third anomaly on March 8 at 11:36. Then, the ΔG value is reduced by 55 units and remains unchanged until March 12, 20:33, after which it is increased by 60 units. Thus, approximately 15 hours after the moment of decreasing of ΔG, there occurs a strong foreshock on March 09, 2011 at 02:45UTC. Then on March 11, 2011 at 05:46 UTC there occurs a strong earthquake with M9.0 and 29 minutes later the second strong earthquake (aftershock) with M7.9 occurs. The last strong aftershock occurs on March 22, 2011 at 07:18UTC. Thus, if we do not consider the weak foreshocks and aftershocks, four strong tremors occur in the epicentre zone.

Meanwhile, as it can be seen on the gravitogram, the gravitational anomalies of *1*, *2*, *3* were recorded before first three earthquakes. Then we see a decrease in the value and a straight line from 8 to 12 March, after which three nearby anomalies were registered again: *1′*, *2′* and *3′*. Thus, we can assume that the anomalies *1*, *2*, *3* are the precursors of earthquakes, and the anomalies *1′*, *2′* and *3′* are secondary and were formed as a result of the release of powerful tectonic energy from three strong earthquakes. Between the primary and secondary anomalies, a straight line has been registered, which persists for four days. On March 18, another very intense gravitational anomaly *4* is recorded, after which the value of ΔG is increased by 60 units and remains unchanged until March 22. At the moment of the end of the straight line and the beginning of the next gravitational anomaly, the fourth strong shock takes place, after which, about five hours later, an intense negative anomaly *4′* was recorded. Thus, gravitational anomaly *4* is a precursor of earthquake *4*, and gravitational anomaly *4′* is a secondary anomaly from earthquake *4*. We see that again between the primary and secondary anomalies a straight line is registered, which persists for four days.

Analysis of the gravitogram of the earthquake Sumatra, April 06, 2010. The recordings of gravitogram before, during and after Sumatra earthquake was done by the ATROPATENA-ID station (Fig. 2, *b*, *g*). The record shows that a straight line was recorded from March 19 to March 29, and since March 29 the station had registered an increase of ΔG by 135 units, after which four intense impulses are registered until 04 March, then again a direct line is observed until March 09, 22:32.

Then, on April 10, we observe a sharp negative impulse ΔG with a decrease by 65 units after which ΔG is restored to its previous level and immediately afterwards a positive impulse was registered with an increase of ΔG by 40 units. Then the value returns to its previous position and from April 10 a direct line is registered again until the end of observations on April 23, 2010.

A strong earthquake M7.8 occurred on April 06 during the recording of a straight line. Thus, we believe that gravitational anomalous impulses *1*—*4* are the precursors of the strong Sumatra earthquake, and we take the most intense impulse *3* as the precursor of the main shock, and the ΔG impulses *1*, *2* and *4* are precursors of two foreshocks and aftershock. At the same time, the impulses *1′* and *2′* are secondary impulses. As in the previous case, a straight line is recorded between gravitational precursors of earthquake and secondary impulses within 5 days.

Analysis of gravitogram of the earthquake Samoa, September 29, 2009, M8.1. The recording of gravitograms before, during and after Samoa earthquake was done by the ATROPATENA-ID station (Fig. 2, *c*, *h*). The record shows that from September 7 to September 10, 2009 a direct line was recorded and starting from September 10 the station registered an increase of Δ*G* by 20 units, after which a direct line is registered again until September 12, 17:30, after which five intensive anomalies Δ*G* were registered.

Beginning from September 15, 22:17, a direct line is registered until October 1, 2009. Meanwhile, on September 29, there occurs a strong earthquake with M8.1, after which since October, 1 five anomalous impulses Δ*G* *1′—5′* are successively recorded.

We see that, in amplitude the impulses *1—5* roughly correspond to the impulses *1′—5′*, while impulses *3* and *3′* are the most intense and have the same amplitude of about 85 units. In our opinion, impulse *3* is a precursor of an earthquake, and the impulse *3′* is a secondary impulse as a result of the isolation of tectonic energy during the earthquake. In this case, impulses *1*, *2*, *4* and *5* are precursors of two foreshocks and two aftershocks, and the impulses *1′*, *2′*, *4′* and *5′* are secondary impulses release of two foreshocks and two aftershocks. As in the previous gravitogram records, we had been observing a direct line between the primary and secondary impulses Δ*G* for 15 days. Then the value of Δ*G* again increased by 50 units and remained unchanged from 10 to 13 August, after which two intense negative impulses Δ*G* were recorded, the latter with a decrease by 72 units.

Analysis of the gravitogram of the earthquake Andaman, August 10, 2009, M7.5. The gravitogram recording before, during and after Andaman earthquake was done by the ATROPATENA-ID station (Fig. 2, *d*, *i*). The record shows that from 01 to 06 August 2009 a direct line was recorded, and starting from August 6 the station registered four intensive anomalies Δ*G*.

On August 08 at 21:37 the Δ*G* value was reduced by 65 units and remained at this level with minor variations until August 9, 10:32, after which it rises by 35 units. On August 09, from 22:05 to 00:00 the Δ*G* impulse was registered with an increase in the level by 23 units, after which the value returned to its previous position. During this impulse, a strong earthquake occurs on August 10 with M7.5.

Thus, we assume that the most intense anomaly *2* on Fig. 2, *i*, is the precursor of the main shock. Anomalies *1*, *3* and *4* are precursors of weak foreshocks and aftershocks. Anomalies *1′* and *2′* Δ*G* in Fig. 2, *i* are secondary and appeared as a result of the released tectonic energy during the earthquake and aftershock. As in the previous cases, the direct line was also registered between the primary and secondary anomalies from 10 to 13 August.

Analysis of gravitogram of the Sichuan earthquake, May 12, 2008, M7.9. Recording the gravitograms before, during and after the Sichuan earthquake was done by the ATROPATENA-AZ station (located in Baku, Azerbaijan) (Fig. 3). The distance between the epicenter and the ATROPATENA-AZ station is 4850 km.

Table 2 shows the parameters of a strong earthquake in Sichuan, as well as previous and subsequent shocks.

Since April 25, 2008, ATROPATENA-AZ stations have registered three-dimensional gravitational anomalies ΔG_x and ΔG_y indexes which is the difference between the gravitational constant *G* (initially measured *G* value) and measured values of the Cavendish balance at the measurement time G_F in two mutually perpendicular directions (Δ*g* — variations of the relative values of gravity (the values after the decimal point are shown mGal).

Analysis of the first channel of gravitogram (Fig. 4) of the Sichuan earthquake shows that since April 24, 2008 to April 30, 2008, seven intense gravity anomalies — the ΔG_x index, have been recorded. In the subsequent period from 01.05.2008 till 05.05.2008 there are no anomalies and starting from 05.05.2008 the values of the ΔG_x index are reduced by 10 conventional units and remain unchanged

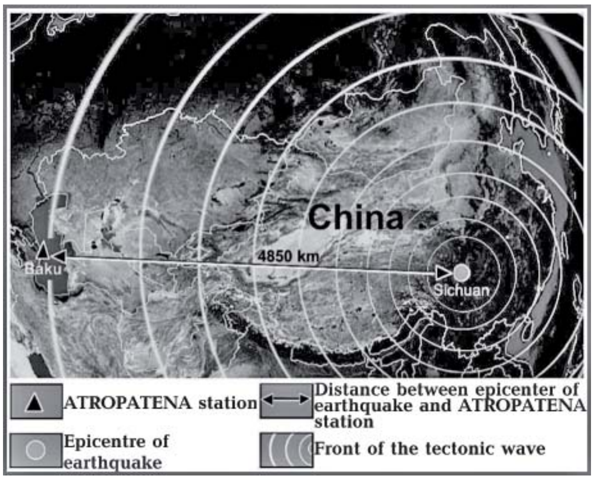

Fig. 3. Map of the distribution of tectonic waves in the region of research.

Table 2. Earthquakes parameters in Sichuan

No	Date, time (UTC)	Location	Depth, km	Magnitude
1	May 12, 2008, 06:28:01	31.002°N, 103.322°E	19.0	7.9
2	May 12, 2008, 06:41:56	31.586°N, 104.032°E	10.0	5.7
3	May 12, 2008, 06:42:08	31.342°N, 104.682°E	10.0	5.7
4	May 12, 2008, 06:43:14	31.211°N, 103.715°E	10.0	5.8
5	May 12, 2008, 11:11:02	31.214°N, 103.618°E	10.0	6.1
6	May 13, 2008, 07:07:08	30.890°N, 103.194°E	9.0	5.8
7	May 17, 2008, 17:08:25	32.240°N, 104.982°E	9.0	5.8

up to 12.05.2008, after which the value of the index increases to the previous value. At the time of index recovery, one strong earthquake occurs: with M7.9 in Sichuan, China on May 12, 2008 (time 06:28:01) and four strong aftershocks (No 2—5 in table 2).

Then two more strong earthquakes occur in this epicentre zone: with M5.8, 13 May 2008 and with M5.8, 17 May 2008. From 12 to 13 May can see seven minor secondary anomalies on the gravitogram (*1′*—*7′*).

Also, between the primary and secondary anomalies, we observe two straight lines, which persist from 01.05 to 05.05 and from 05 to 12 May 2008.

Analysis of the records of the second channel shows that from April 24, 2008 to April 29, 2008, six gravity anomalies were recorded — the ΔG_y index, with a smaller amplitude, compared to the recording of the first channel. These anomalies are precursors of the Sichuan earthquakes.

In the subsequent period till 08.05.2008 there are no anomalies and starting from 06.05.2008 the values of the ΔG_y index decrease by three conventional units and remain unchanged up to 12.05.2008, after which the index value increases by two conventional units and we observe seven secondary anomalies in the period from 12.05.08 to 16.05.08. The authors consider that these anomalies are not precursors of earthquakes, but they are secondary ones and occur as a result of the release of powerful tectonic energy at strong earthquakes and aftershocks. At the moment of index ΔG_y recovery one strong earthquake occurs: with M7.9 in Sichuan, China on May 12, 2008 (time 06:28:01) and four strong aftershocks (No 2—5 in table 2).

Then two more strong earthquakes occur in this epicentre zone: with M5.8, 13 May 2008 and with M5.8, 17 May 2008. From 12 to 13 May can see seven minor secondary anomalies on the gravitogram (*1′*—*7′*).

As it can be seen on the recording of the second channel, from 12 to 17 May, the authors identified seven gravitational anomalies. According to the authors, these anomalies are the result of strong earthquakes and aftershocks, which occurred in the epicentre zone of Sichuan earthquake during this period of time.

Thus, we single out two types of gravitational anomalies on the second channel. The first type of anomalies — the precursors and the second type of anomalies — arise as a result of earthquakes that have already occurred.

Analysis of gravitograms of the third channel. Let's consider the record of the third channel, which characterizes Δg — variations of the relative values of gravity (the values after the decimal point are shown). These anomalies have been recorded by a special

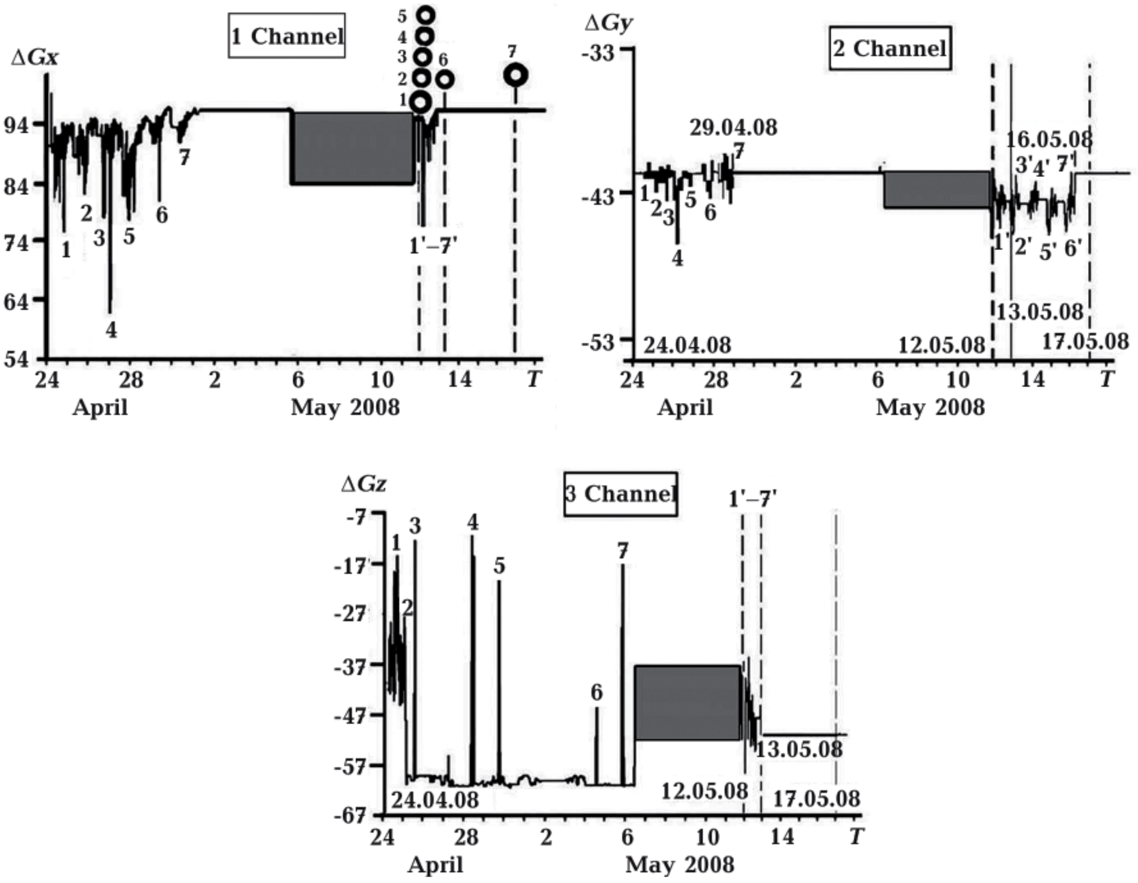

Fig. 4. Records of the first, second and third channels of the ATROPATENA station; ΔG_x and ΔG_y — indexes which is the difference between the gravitational constant G (initially measured G value) and measured values of the Cavendish balance at the measurement time — G_F in two mutually perpendicular directions; *Ag* — variations of the relative values of gravity/the values after the decimal point are shown; *1*—*7* — numbers of gravitational precursors; *1′*—*7′* — numbers of the Sichuan earthquakes.

gravimeter of the ATROPATENA station. We have identified seven intensive anomalies in the record from 24.04.2008 to 06.05.2008, after which the value of Δg significantly increases by 2,3 mGal. This value remains unchanged till 12.05.2008, after which it drops sharply by 1,2 mGal. In the period from 12.05.2008 to 13.15.2008, seven secondary anomalies of smaller amplitude were recorded. Starting from 13.05.2008, the Δg value is stabilized and no anomalies are recorded.

Results of gravitogram analysis. It should be noted that analyses of more than 100 gravitograms records by ATROPATENA stations before, during and after strong earthquakes in other regions of the world in the periods from 2008 to 2011 allowed confirming registration of gravitational precursors before strong earthquakes [Sobolev et al., 2008; Khalilov, 2009]. The first type are anomalies before strong earthquakes — they are precursors of earthquakes and the second type are anomalies after strong earthquakes (secondary anomalies), which are formed as a result of radiation of tectonic waves at the time of the earthquake and release of tectonic energy. Between these two types of anomalies, in the overwhelming majority of cases, a long-term gravitational anomaly with the increased or decreased value of the ΔG index and *Ag*, which remains stable, usually for 2—15 days, is recorded. These characteristic features of gravitational anomalies on the records of gravitograms before, during and after strong earthquakes are observed in more than 90 % of cases.

According to the authors' opinion, which is supported by the results of numerous experiments, the gravitational precursors of strong earthquakes are the result of the emission of tectonic waves (stress waves) by earthquake centers 2—10 days before the earthquake [Sobolev et al., 2008; Khalilov, 2009]. The time of registration of gravitational precursors of strong earthquakes also depends on the distance of the ATROPATENA station to the epicenter. The periods of three-dimensional gravity anomalies vary from 10 minutes to 10—12 hours and depend on the geological structure of the epicenter zone. It should be emphasized that the seismic stations that are included in the set of all ATROPATENA stations of earthquake forecasting do not register any anomalous seismic signals during the registration of gravitational precursors. The authors came to a very important conclusion: ΔG index and Ag they are universal precursors of earthquakes and are recorded in more than 90 % of cases.

Possible physical model. What physical model of manifestation of gravity anomalies can be considered for these experiments? Currently, in our view, the most optimal is the model based on emission of slow stress waves (tectonic waves) from the focus of an imminent earthquake immediately before the shock. The possibility of existence of slow mechanical waves in the lithosphere has been shown theoretically in the works [Elsasser, 1969; Lehner et al., 1981] and other studies. Researches by some authors confirm the possibility of formation in the lithosphere of slow tectonic waves, which are sometimes called stress waves or lithosphere waves [Keilis-Borok, 1999; Gorbunova, Sherman, 2012].

Subsequent research and works by E. N. Khalilov corroborate the generation of these waves by the focuses of imminent strong earthquakes and possibility of recording them with the use of the Cavendish balance. Besides, there are some features in the ATROPATENA station records that can evidence of the wave origin of the observed gravity anomalies [Khalilov, 2009; Khalilov et al., 2011]. As the distance between the recording station and the earthquake's epicenter grows, less high-frequency gravity anomalies and appearance of low-frequency anomalies can be observed [Khalilov et al., 2011].

Let us consider the process of rupture of a crust fragment during the motion of tectonic blocks along the fissure plane as a possible model for the generation of tectonic waves before strong earthquakes. Fig. 5, *a* shows a fragment of the Earth's crust with a fissure before the deformation process. Fig. 5, *b* pictures the moment when crustal blocks move relative to each other on the fissure plane at the time of plastic deformation. Plastic deformation precedes the rupture of a continuous medium and is accompanied by alternating voltage which can be a source of stress waves or tectonic waves. At a certain moment of plastic deformation and motion of tectonic blocks, the breaking point for crustal blocks adhesion strength is reached, followed by a rupture and abrupt movement of the crustal blocks leading to emission of seismic waves and an earthquake as shown in Fig. 5, *c*. Given that the plastic strain rate is much lower than the rate of motion of the tectonic blocks at the moment of rupture, in the plastic deformation zone there can be formed slow mechanical waves, that is, tectonic waves (stress waves). Plastic deformation of a medium is accompanied by destruction processes, forming of minor cracks which grow and join together as the deformation continues. The formation of cracks leads to emergence of hi-frequency seismic waves.

That is why station 1, the closest to the epicenter of the Japanese earthquake of March 11, 2008 registered high-frequency oscillations which were decaying with the increasing distance from the epicenter. Stations more distant from the epicenter could only record very low-frequency components of the tectonic wave spectrum [Khalilov et al., 2011].

Fig. 6 show the dependence of the value of deformation of the earth's layers on the growth of mechanical stresses.

At the time of the destruction of the medium, along with seismic waves, secondary tectonic waves are also emitted. Secondary tectonic waves are recorded by ATROPATENA stations in the form of secondary gravitational anomalies.

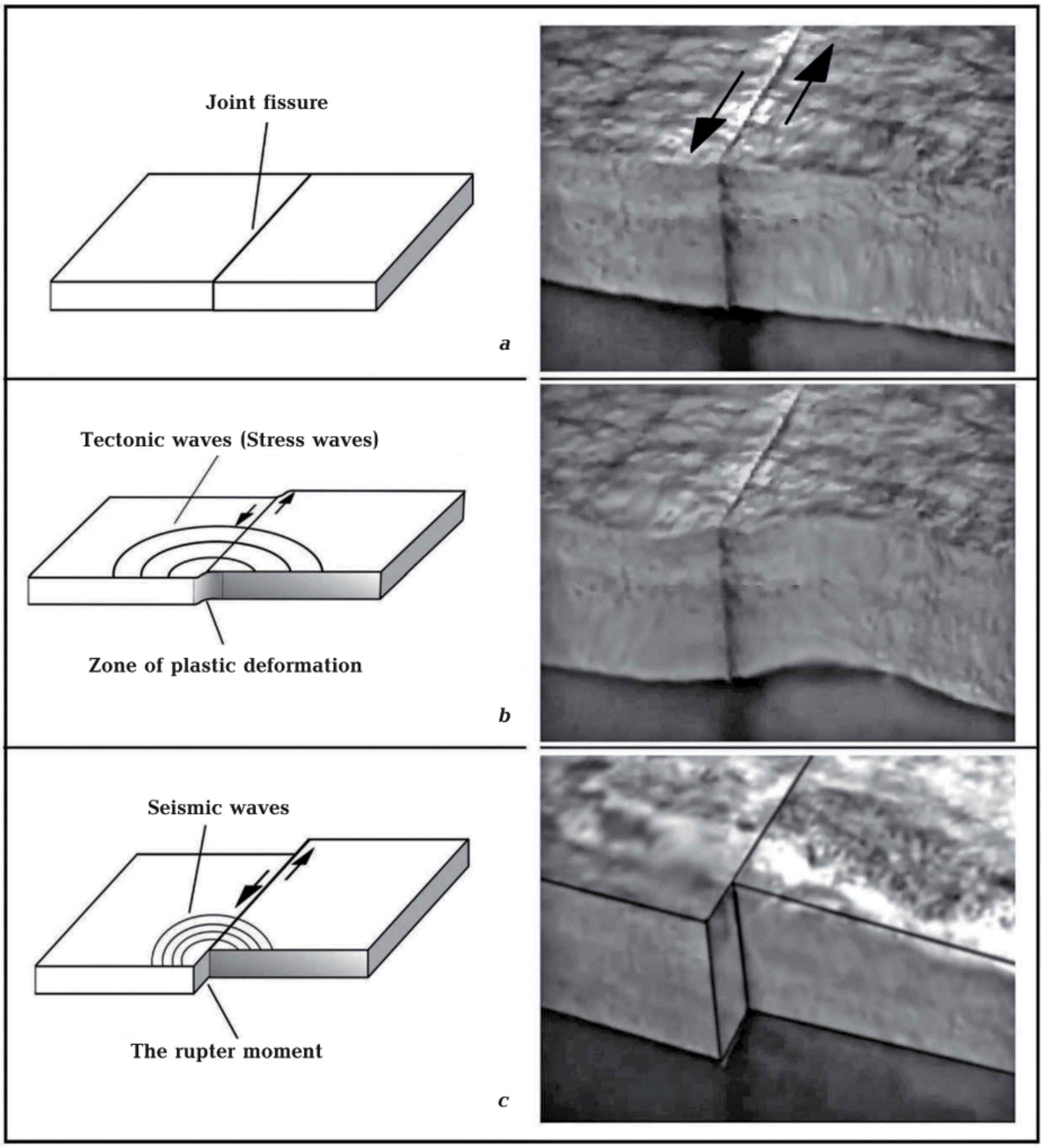

Fig. 5. Tectonic wave generation model: *a* — crust fragment with a fissure; *b* — movement of crust blocks along the fissure at the moment of plastic deformation; *c* — moment of rupture and movement of tectonic blocks along the fissure.

Conclusions. The conclusions drawn by the authors can be divided into two categories: experimental results and the model proposed by the authors.

1. *Experimental results.* To monitor spatiotemporal variations of the gravitational field, special detectors named ATROPATENA stations have been developed and made. The detectors continuously measure the value of the gravitational constant G in mutually perpendicular directions and relative values of gravity Δg.

Before and after the Mega Earthquakes in Asia and Southeast Asia, variations of the Earth's gravitational field were registered at large distances from the epicenter (near

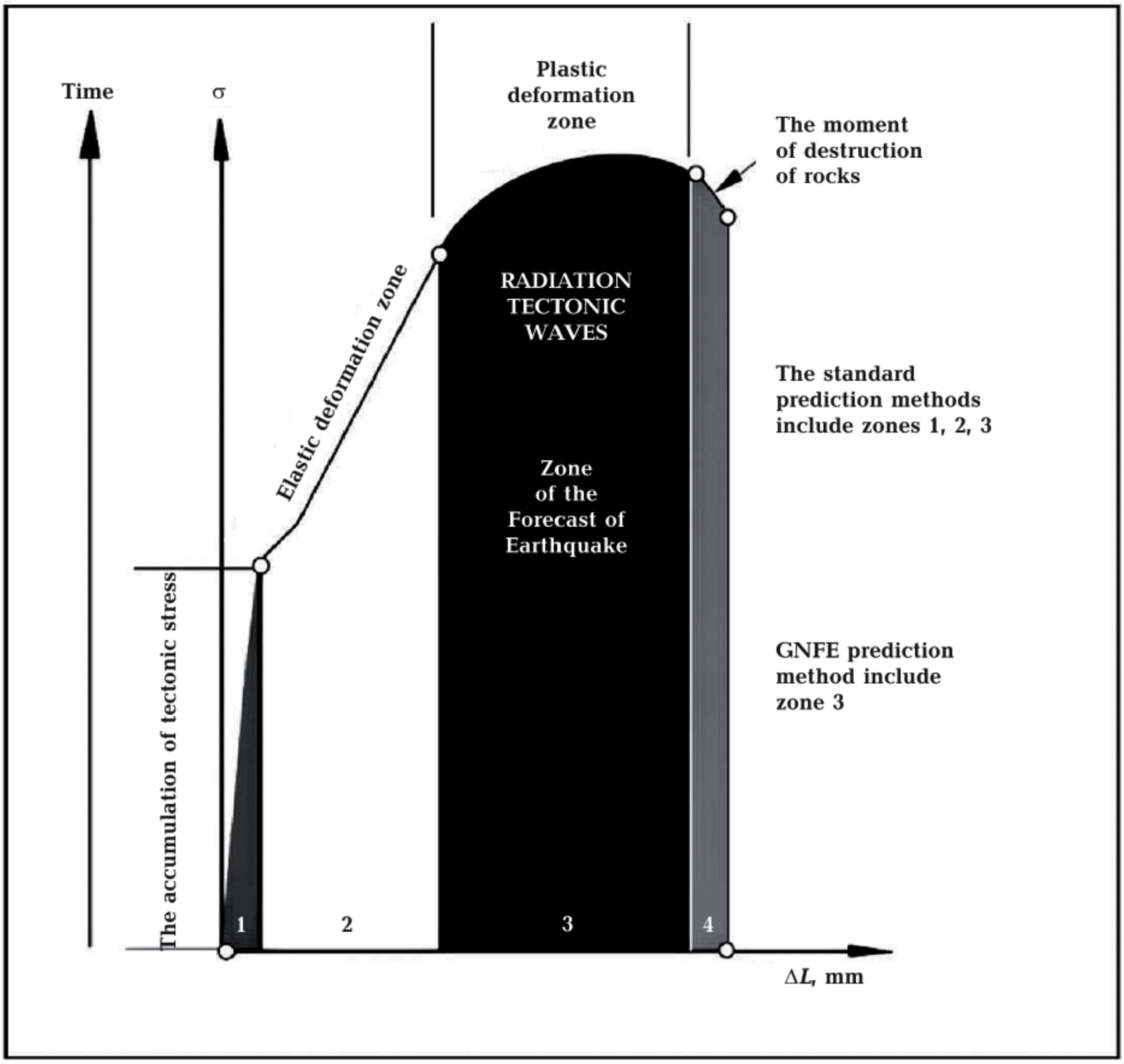

Fig. 6. Graph of the dependence of the value of deformation of the earth's layers on the growth of mechanical stresses. Black zone shows the formation of tectonic waves.

8000 km); they were measured with the ATROPATENA stations in the following location: Baku (Azerbaijan) and Yogyakarta (Indonesia).

Indications of the Cavendish balance when measuring the gravitational constant *G* are influenced by spatio-temporal changes in external gravitational fields of geological origin, which alter over time indications of the true values of *G*.

Measuring the true value of the gravitational constant *G* on the Earth's surface with accuracy greater than the second digit after the decimal point is not possible due to the spatio-temporal variations of the gravitational field as a result of the impact of geodynamic processes.

For the first time, the true cause of variations of the recorded values of the gravitational constant *G* has been identified. These variations were the subject of scientific dispute throughout the last century.

2. *Model.* The authors propose a model of emission of slow tectonic waves (stress waves) in the focal region of an imminent earthquake as a result of plastic deformation of crustal layers immediately before the rup-

ture (abrupt displacement). Tectonic waves are a sort of mechanical waves, altering the density of crust layers in the motion process. Alternating changes in the density of the earth crust layers lead to periodic changes of the mass and, as a consequence, of the gravitational field within of the tectonic wave. The monitoring of spatio-temporal changes in the gravitational field can be carried out using special devices consisting of the mutually perpendicular Cavendish balance and gravimeter (ATROPATENA stations).

The main conclusion. Over the years, geophysicists have been trying to find a universal precursor of earthquakes. They studied more than 300 types of earthquake precursors, but none of them was universal. Each of the known precursors arose in 50—65 % of the cases before the earthquake. This became one of the main reasons for failures in forecasting earthquakes. The authors believe that the detected tectonic waves with the help of ATROPATENA earthquake forecasting stations are a universal precursor of earthquakes, since they are emitted in all cases during the plastic deformation just before the destruction of rocks.

Analysis of global gravitational precursors before some Asian strong earthquakes

E. Khalilov*[1]*, L. Wang*[2]*, L. Khalilova*[3]*, 2019

The authors consider the gravitational precursors of Mega Earthquakes in Asia and Southeast Asia: Sichuan earthquake, M7.9, May 12, 2008; Andaman Islands earthquake, M7.5, August 10, 2009; Samoa Islands earthquake, M8.1, September 29, 2009; Northern Sumatra earthquake, M7.8, April 06,2010; Tohoku earthquake, M9, March 11, 2011. All gravitational precursors were recorded using of ATROPATENA earthquake prediction stations. The creation of an international earthquake prediction system based on the results obtained is proposed. To monitor spatio-temporal variations of the gravitational field, special detectors named ATROPATENA stations have been developed and made. The detectors continuously measure the value of the gravitational constant G in mutually perpendicular directions and relative values of gravity Δg. Before and after the Mega Earthquakes in Asia and Southeast Asia, variations of the Earth's gravitational field were registered at large distances from the epicenter (near 8000 km); they were measured with the ATROPATENA stations in the following location: Baku (Azerbaijan) and Yogyakarta (Indonesia). Indications of the Cavendish balance when measuring the gravitational constant G are influenced by spatio-temporal changes in external gravitational fields of geological origin, which alter over time indications of the true values of G. Measuring the true value of the gravitational constant G on the Earth's surface with accuracy greater than the second digit after the decimal point is not possible due to the spatio-temporal variations of the gravitational field as a result of the impact of geodynamic processes.

For the first time, the true cause of variations of the recorded values of the gravitational constant G has been identified. These variations were the subject of scientific dispute throughout the last century.

Key words: earthquake prediction, gravitational precursors, tectonic waves, ATROPATENA station, seismology, geodynamics, geotectonics.

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