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Tectonic sources of caucasus strong earthquakes

M. Kachakhidze[1], N. Kachakhidze[1], R. Kiladze[2], V. Kukhianidze[2], and G. Ramishvili[2]

[1]Tbilisi State University, Chavchavadze st. 2, Tbilisi 380028, Georgia
[2]Abastumani Astrophysical Observatory, Kazbegi av. 2a, Tbilisi 380060, Georgia

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Abstract. The method called “phase cone” is developed in order to define the location, time of arising and velocity of the earthquakes initiating the low-speed interference stress waves. From the data of the strong earthquakes with $M \geq 6.0$ in Caucasus region during 1900–1992, the immigrators or tectonic sources of low-speed waves were revealed, interference nodes of which had initiated 19 earthquakes out of total 33.

The time of arising of low-speed stress waves or periods of awaking of tectonic sources is defined.

The velocities of constant initiative waves for all events were calculated. Its average value is equal to 2.97 km per year.

1 Introduction

If there were no variable strains in the Earth, the earthquakes would occur the very moment the strain in the zone of preparing of earthquakes reached its critical value – the limit of solidity of geological surroundings.

The presence of variable strains in the Earth changes this picture a lot. These strains, added up to the main tectonic stress, can lead the total stress to its critical value prematurely and thus initiate subsequent earthquake in the earlier stage of its preparing (Amazigo et al., 1976; Anderson, 1985; Du et al., 2003; Gomberg, 1996; Hill et al., 1993; Lehnez et al., 1981; Mogi, 1973; Nikonov, 1976).

Among such endogenous initiating factors, there are the strains arising in the Earth crust during the earthquakes and by active tectonic stress embryos as well. The available theoretical studies offer different models of possibilities of appearance and distribution of anomalously low-speed tension waves, which on their route of distribution facilitate the appearance of earthquakes (Bott, 1983; Brodsky et al., 1999; Jadin, 1984; Kelleher, 1970; McGinty et al., 2001; Savage, 1971; Shapiro et al., 2003).

Under the complex geological processes such active tectonic sources can be awaken and radiate low-speed waves. On their way the waves can become triggering factors for subsequent earthquakes.

Based on the data of strong earthquakes in Caucasus region, the method of “phase cone” allows us to reveal such possible tectonic sources.

2 The method

Let’s consider, that at some moment in the place with geographical coordinates λ_0 and φ_0 (longitude and latitude accordingly), a spherical wave extending in all directions with constant speed v was born.

When this wave at some moment t reaches a point of a potential seismic center (we shall designate its coordinates through λ and φ), there is an initiation of the earthquake (Fig. 1).

Obviously, in order to find four unknown variables ($t_0,\ \lambda_0,\ \varphi_0$ and v), four equations are needed.

We designate the variables as $t_i,\ \lambda_i,\ \varphi_i,$ where $i=1,\ 2,\ 3,\ 4$.

For the solution of the problem it is more convenient to use rectangular coordinates x, y on a surface of the Earth, where the x-axis is directed to the East, and y-axis – to the North. We choose the center of coordinates at some point near the center of the region; let its geographical coordinates be L and Φ.

In this case, if the investigated region is small enough, there are the simplified dependences (Blajko, 1979):

$$x_i = R(\lambda_i - L)\cos\varphi_i$$
$$y_i = R(\varphi_i - \Phi) \qquad (1)$$

Correspondence to: M. Kachakhidze
(manana_k@hotmail.com)

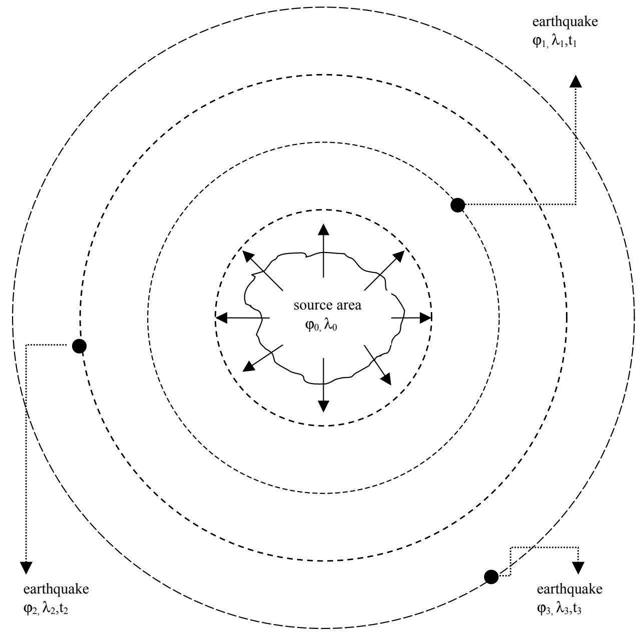

Fig. 1. Potential seismic area.

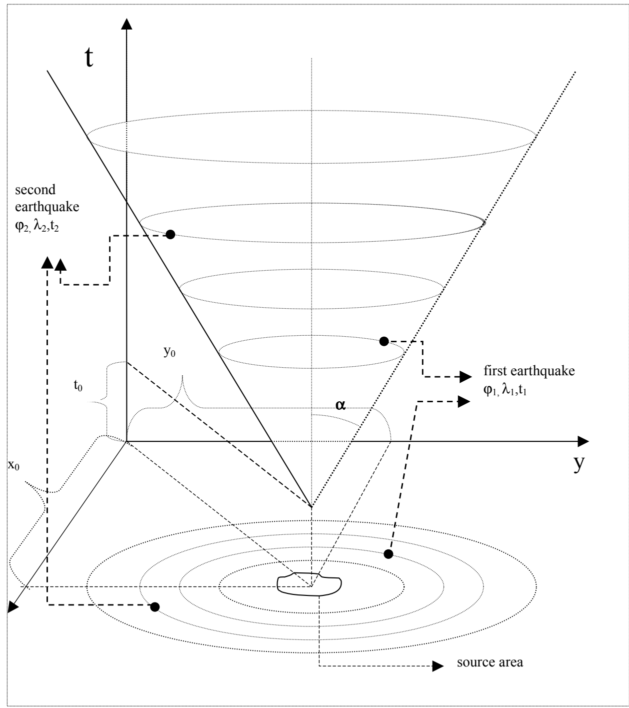

Fig. 2. Phase cone.

and also

$$\lambda_i = L + \frac{x_i \sec \varphi_i}{R}$$
$$\varphi_i = \Phi + \frac{y_i}{R} \qquad (2)$$

For the earthquake number i we shall write down:

$$\sqrt{(x_i - x_0)^2 + (y_i - y_0)^2} = \nu (t_i - t_0) \qquad (3)$$
$$i = 1, 2, 3, 4$$

this equation can be reduced to the cubic one, which always has at least one solution (see Appendix).

One can assign the following geometrical sense to the problem. Let's construct the three-dimensional coordinate system x, y, t to each earthquake in the phase space, corresponding to a certain point. The distribution of a wave in this space will be described by a cone, the axis of which is parallel to t-axis, and the angle of a cone (α) is determined by the speed of wave of a stress from the immigrator. The points corresponding to the earthquakes, initiated by a wave, will lay on the surface of this cone (Fig. 2).

It follows from the described procedure of the solution of the problem, that on every group of four points in our phase space it is possible to construct a cone (sometimes – 3 cones in case if the cubic equation has three roots). The top of such a cone will correspond to the coordinates (x, y) of the immigrator and the moment (t) of birth of a trigger wave of a stress.

3 Discussion

We studied the Caucasus strong earthquakes with during 1900–1992 (Table 1). By "phase cone" method it was possible to reveal the large Caucasus earthquakes, which were initiated in the interference nodes by the low-speed radiated waves from the immigrators.

The initiated earthquakes are presented by separate groups. The groups with the earthquake number from 4 to 7, gave us plenty of scattered picture of the immigrator (or the cone tops) distribution throughout the Caucasus map.

The reliable picture has been obtained for the groups with the earthquake numbers from 8 to 11. For these groups the cone tops throughout the Caucasus seismoactive territory are distributed near the four points. The immigrators or cone tops are pointed by triangles in the Fig. 3.

The analysis of the results lets us draw the following: Two immigrators out of 4 with coordinates φ=41.28°; λ=45.3° and φ=39.28°; λ=46.31° are presented as separate sources. They appeared 97 and 95.9 years before the first large earthquake (13 February 1902) of the last century. The third immigrator consists of three cone tops, which are located almost at the same point (φ=39.96°−40.0°; λ=46.03°−46.04°). According to calculation, this sources of stress woke up 71–70.4 years before the same 13 February 1902 earthquake, i.e. we had "pulsation" of tectonic source with the period of 14 years.

The fourth accumulation of the immigrators is considerable. In this case, in a very narrow strip (φ=40.51°−40.61°; λ=47.33°−47.47°) 61 cone tops coincide. This is the same location of immigrators, which acted for 11.2 years, according to calculation we have obtained the moments of arising of stress triggering waves 40.9 and 29.7 years before the 13 February 1902 earthquake.

Table 1.

N	Year	Month	Data	latitude (φ)	longitude (λ)	magni-tude
1	1902	2	13	40.7	48.6	6.9
2	1905	10	21	43.3	41.7	6.4
3	1911	6	7	41	50.5	6.4
4	1920	2	20	42	44.1	6.2
5	1924	2	19	39.4	48.6	6.6
6	1924	9	13	40	42	6.9
7	1930	5	6	38.1	44.6	7.3
8	1931	4	27	39.2	46	6.3
9	1931	10	20	42.5	50.8	6.2
10	1935	4	9	42.1	48.8	6.3
11	1935	5	1	40.4	43.4	6.2
12	1939	12	26	39.7	39.7	8
13	1940	5	7	41.7	43.8	6
14	1942	12	20	40.7	36.8	7
15	1948	6	29	41.9	46.8	6.1
16	1949	8	17	39.4	40.9	6.7
17	1957	7	2	36	52.5	6.5
18	1961	9	18	41.066	50.233	6.6
19	1963	1	27	41.08	49.84	6.2
20	1963	7	16	43.18	41.65	6.4
21	1966	8	19	39.166	41.55	6.8
22	1970	5	14	43	47.083	6.6
23	1971	5	22	38.85	40.516	6.8
24	1976	7	28	43.17	45.6	6.2
25	1976	11	24	39.1	44	7
26	1978	11	4	37.61	49.04	6
27	1980	5	4	37.8	49.1	6.2
28	1983	10	30	39.983	41.6	6.8
29	1986	3	6	40.06	51.63	6.1
30	1988	12	7	40.9	44.2	6.9
31	1989	9	16	40.34	51.6	6.3
32	1991	4	29	42.39	43.68	6.9
33	1992	10	23	42.49	44.99	6.3

Table 2.

N	T	φ	λ	V	Numeration of Initiated Earthquakes Distance till Immigrators (km)										
1	−97	41.3	45.3	2.9	1	5	7	16	23	26	27	31			
					284	349	359	427	489	519	506	540			
2	−95	39.3	46.3	2.6	1	13	18	21	22	24	29	31			
					251	343	388	410	419	437	463	467			
3	−71	40	46	2.5	5	7	13	22	24	26	27	28			
					229	243	268	346	356	371	360	378			
4.1	−40	40.6	47.4	2.85	1	5	8	10	24	25	27	31	32		
					103	165	193	207	326	332	341	357	370		
4.2	−36	40.6	47.4	2.96	1	5	8	10	24	25	27	29	31	32	
					103	165	193	207	326	332	341	364	357	370	
4.3	−33	40.6	47.4	3.1	1	5	8	10	24	25	26	27	29	31	32
					103	165	193	207	326	332	358	341	364	357	370

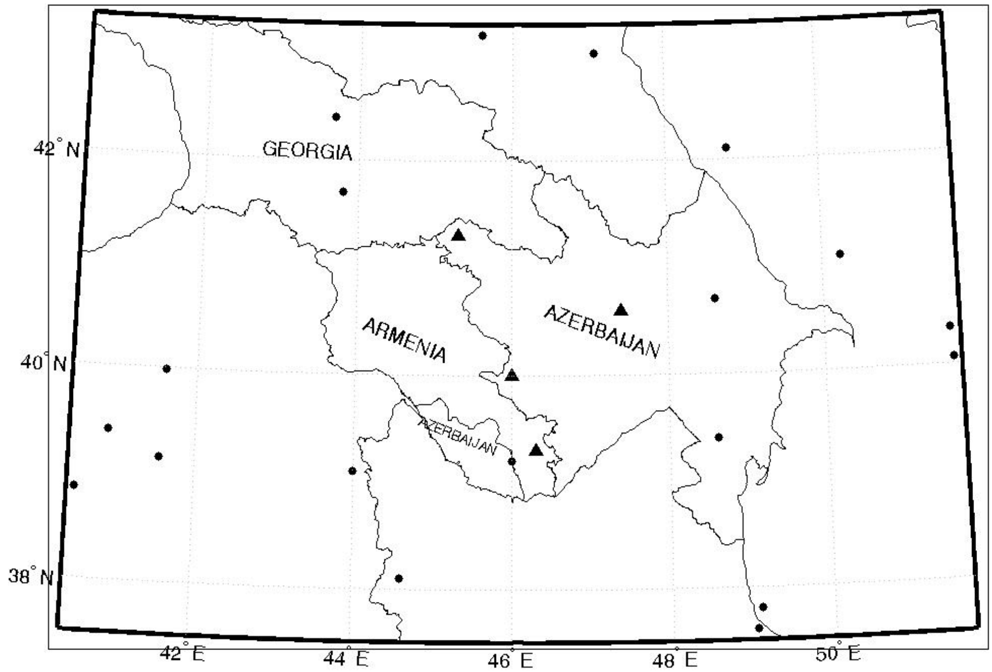

Fig. 3. Location of strong earthquakes and immigrators (cone tops) throughout the Caucasus seismoactive region (black circle – earthquakes; black triangle – cone tops.

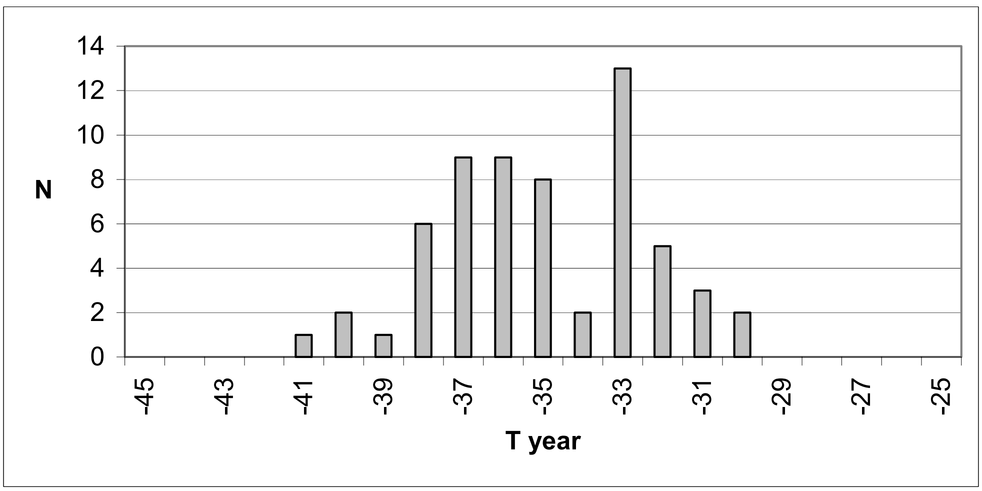

Fig. 4. Histogram of initiative waves arising moments for three subgroups of immigrators.

We carefully studied this group and came to conclusion that this group is divided into three subgroups, by the moments of arising – 4.1, 4.2, 4.3 (Table 2). In the histogram three subgroups of arising moments of initiative waves are presented –33, –36 and –40 years before 13 February 1902 earthquakes (Fig. 4).

As it was pointed out above, for the fourth immigrator we have a coincidence of 61 cone tops during 11.2 years. By the Fourier analysis, for the immigrator awaking period we found 1.7 year.

By the stress waves in the interference nodes with the four defined immigrators 19 earthquakes out of 33 were initiated.

As was expected, the earthquakes are located at any distance and in any direction from the immigrators.

We must point out that all the immigrators initiate earthquakes by the stress waves with almost constant velocity. The value of the stress wave velocity vary from 2.5 to 3.1 km per year. The average velocity is equal to 2.97 km per year.

In the Table 2 the final results of calculations are given. There is the list of immigrators (N) and initiated earthquakes (numeration of earthquakes are according to the Table 1). The Table 2 contains the coordinates of the immigrators, the moments of earthquakes T initiated by the waves aroused towards 13 February 1902 earthquake and their velocities.

Appendix A

$$\sqrt{(x_i-x_0)^2+(y_i-y_0)^2}=\nu(t_i-t_0)\qquad i=1,2,3,4 \tag{A1}$$

Having got rid of radicals in Eq. (A.1) and consistently subtracting the equations one from another, we receive a system of three equations:

$$\begin{aligned}
2\,(t_1-t_2)\,\omega t_0-2\,(x_1-x_2)\,x_0-2\,(y_1-y_2)&=(t_1^2-t_2^2)\,\omega-(x_1^2-x_2^2)-(y_1^2-y_2^2)\\
2\,(t_2-t_3)\,\omega t_0-2(x_2-x_3)\,x_0-2\,(y_2-y_3)&=(t_2^2-t_3^2)\,\omega-(x_2^2-x_3^2)-(y_2^2-y_3^2)\\
2\,(t_3-t_4)\,\omega t_0-2\,(x_3-x_4)\,x_0-2\,(y_3-y_4)&=(t_3^2-t_4^2)\,\omega-(x_3^2-x_4^2)-(y_3^2-y_4^2)
\end{aligned}\tag{A2}$$

where

$$\omega=\nu^2 \tag{A3}$$

The solution of system of the Eqs. (A.2) looks as follows:

$$\begin{aligned}
\omega t_0&=a\,\omega+b\\
x_0&=c\,\omega+d\\
y_0&=e\,\omega+f
\end{aligned}\tag{A4}$$

where

$$a=\frac{1}{D}\begin{vmatrix} t_1^2-t_2^2 & x_2-x_1 & y_2-y_1\\ t_2^2-t_3^2 & x_3-x_2 & y_3-y_2\\ t_3^2-t_4^2 & x_4-x_3 & y_4-y_3\end{vmatrix}$$

$$b=\frac{1}{D}\begin{vmatrix} x_2^2-x_1^2+y_2^2-y_1^2 & x_2-x_1 & y_2-y_1\\ x_3^2-x_2^2+y_3^2-y_2^2 & x_3-x_2 & y_3-y_2\\ x_4^2-x_3^2+y_4^2-y_3^2 & x_4-x_3 & y_4-y_3\end{vmatrix}$$

$$c=\frac{1}{D}\begin{vmatrix} t_1-t_2 & t_1^2-t_2^2 & y_2-y_1\\ t_2-t_3 & t_2^2-t_3^2 & y_3-y_2\\ t_3-t_4 & t_3^2-t_4^2 & y_4-y_3\end{vmatrix}$$

$$d=\frac{1}{D}\begin{vmatrix} t_1-t_2 & x_2^2-x_1^2+y_2^2-y_1^2 & y_2-y_1\\ t_2-t_3 & x_3^2-x_2^2+y_3^2-y_2^2 & y_3-y_2\\ t_3-t_4 & x_4^2-x_3^2+y_4^2-y_3^2 & y_4-y_3\end{vmatrix}$$

$$e=\frac{1}{D}\begin{vmatrix} t_1-t_2 & x_2-x_1 & t_1^2-t_2^2\\ t_2-t_3 & x_3-x_2 & t_2^2-t_3^2\\ t_3-t_4 & x_4-x_3 & t_3^2-t_4^2\end{vmatrix}$$

$$f=\frac{1}{D}\begin{vmatrix} t_1-t_2 & x_2-x_1 & x_2^2-x_1^2+y_2^2-y_1^2\\ t_2-t_3 & x_3-x_2 & x_3^2-x_2^2+y_3^2-y_2^2\\ t_3-t_4 & x_4-x_3 & x_4^2-x_3^2+y_4^2-y_3^2\end{vmatrix}\tag{A5}$$

where

$$D=2\cdot\begin{vmatrix} t_1-t_2 & x_2-x_1 & y_2-y_1\\ t_2-t_3 & x_3-x_2 & y_3-y_2\\ t_3-t_4 & x_4-x_3 & y_4-y_3\end{vmatrix}$$

By substitution of values ω, t_0, x_0 and y_0, determined by means of Eqs. (A.4) and (A.5), in any (for example, first) equation, Eq. (A.1) will give us the equation, with respect to ω:

$$\begin{aligned}
&\omega^3(c^2+e^2)\\
&+\omega^2(2cd+2ef-2cx_1-2ey_1-t_1^2+2at_1-a^2)\\
&+\omega(x_1^2+y_1^2-2dx_1-2fy_1+d^2+f^2+2Bt_1-2ab)\\
&-\quad b^2=0
\end{aligned}\tag{A6}$$

Let's write down the Eq. (A.6) in a compact form

$$\omega^3+3A\omega^2+B\omega+C=0 \tag{A7}$$

where

$$\begin{aligned}
A&=\frac{2cd+2ef-2ex_1-2ey_1-t_1^2+2at_1-a^2}{3(c^2+e^2)}\\
B&=\frac{x_1^2+y_1^2-2dx_1-2fy_1+d^2+f^2+2bt_1-2ab}{c^2+e^2}\\
C&=-\frac{b^2}{c^2+e^2}
\end{aligned}\tag{A8}$$

Because C≺0, the Eq. (A.7) according to the Descarte's theorem has at least one positive root Exception can take place only in the case b=0 (it is practically impossible).

Hence, the problem always has at least one solution (we remind, according to Eq. (A.3), physical sense has $\omega \succ 0$).

For the further research of the Eq. (A.7) we shall introduce new values z and p, determined by equations:

$$\begin{aligned}
z&=(\omega+A)\left(2A^3-AB+C\right)^{-1/3}\\
p&=(B-3A^2)\left(2A^3-AB+C\right)^{-2/3}
\end{aligned}\tag{A9}$$

then Eq. (A.7) converts into:

$$z^3+pz+1=0 \tag{A10}$$

if

$$P\geq -3\cdot 4^{-1/3}\approx -1.59 \tag{A11}$$

that Eq. (A.7) has one real root, which can be calculated according to formula of Kardano:

$$z = \frac{1}{\sqrt[3]{2}}\left[\left(-1+\sqrt{1+\frac{4}{27}p^3}\right)^{1/3} + \left(-1-\sqrt{1+\frac{4}{27}p^3}\right)^{1/3} \right] \quad \text{(A12)}$$

If the inequality (A.11) is not true, then the Eq. (A.10), and consequently also Eq. (A.7) has three real roots. In such case application of Eq. (A.12) is difficult and it is more preferable to use an iteration method:

$$Z_{n+1} = -\left(pz_n + 1\right)^{-1/3} \quad \text{(A13)}$$

and as initial approach it is possible to accept

$$Z_0 = -\left(p^2 - \frac{4}{3}p + 1\right)^{1/4} \quad \text{(A14)}$$

After specifying one unknown (we shall designate it through z'), other two roots of Eq. (A.10) may be easily calculated from the square Eq. (A.15) obtained by division Eq. (A.10) by $(z - z')$:

$$z^2 + z'z - \frac{1}{z'} = 0 \quad \text{(A15)}$$

whence

$$z = -\frac{z'}{2} \pm \sqrt{\frac{z'^2}{4} + \frac{1}{z'}} \quad \text{(A16)}$$

after finding z it is easy by helping Eq. (A.9) to define the corresponding value of:

$$\omega = -A + \left(2A^3 - AB + C\right)^{1/3} z \quad \text{(A17)}$$

and other unknowns (x_0, y_0, t_0) are determined by the formulas (A.3) and (A.4).

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