RECENT GEODYNAMICS

MIGRATION OF SEISMIC AND VOLCANIC ACTIVITY AS DISPLAY OF WAVE GEODYNAMIC PROCESS

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Abstract: Publications about the earthquake foci migration have been reviewed. An important result of such studies is establishment of wave nature of seismic activity migration that is manifested by two types of rotational waves; such waves are responsible for interaction between earthquakes foci and propagate with different velocities. Waves determining long-range interaction of earthquake foci are classified as Type 1; their limiting velocities range from 1 to 10 cm/s. Waves determining short-range interaction of foreshocks and aftershocks of individual earthquakes are classified as Type 2; their velocities range from 1 to 10 km/s. According to the classification described in [Bykov, 2005], these two types of migration waves correspond to slow and fast tectonic waves.

The most complete data on earthquakes (for a period over 4.1 million of years) and volcanic eruptions (for 12 thousand years) of the planet are consolidated in a unified systematic format and analyzed by methods developed by the authors. For the Pacific margin, Alpine-Himalayan belt and the Mid-Atlantic Ridge, which are the three most active zones of the Earth, new patterns of spatial and temporal distribution of seismic and volcanic activity are revealed; they correspond to Type 1 of rotational waves. The wave nature of the migration of seismic and volcanic activity is confirmed. A new approach to solving problems of geodynamics is proposed with application of the data on migration of seismic and volcanic activity, which are consolidated in this study, in combination with data on velocities of movement of tectonic plate boundaries. This approach is based on the concept of integration of seismic, volcanic and tectonic processes that develop in the block geomedium and interact with each other through rotating waves with a symmetric stress tensor. The data obtained in this study give grounds to suggest that a geodynamic value, that is mechanically analogous to an impulse, remains constant in such interactions. It is thus shown that the process of wave migration of geodynamic activity should be described by models with strongly nonlinear equations of motion.

Key words: migration, waves, rotation, seismicity, volcanism, geodynamics, conservation law, rheidity.

МИГРАЦИЯ СЕЙСМИЧЕСКОЙ И ВУЛКАНИЧЕСКОЙ АКТИВНОСТИ КАК ПРОЯВЛЕНИЕ ВОЛНОВОГО ГЕОДИНАМИЧЕСКОГО ПРОЦЕССА

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Аннотация: Проведен обзор работ по миграции очагов землетрясений. Важным результатом явилось установление волновой природы миграции сейсмической активности, которая осуществляется двумя типами ротационных волн, ответственными за взаимодействие очагов землетрясений и распространяющимися с разными скоростями. Первому типу с предельными скоростями 1–10 см/с соответствуют волны, определяющие дальнодействующее взаимодействие очагов землетрясений, второму – с предельными скоростями 1–10 км/с – соответствуют волны, определяющие близкодействующее взаимодействие форшоков и афтершоков в пределах отдельно взятых очагов землетрясений. Согласно классификации [Bykov, 2005], такие типы волн миграции соответствуют медленным и быстрым тектоническим волнам.

В едином формате представлены наиболее полные данные о землетрясениях за 4.1 тыс. лет и извержениях вулканов за 12 тыс. лет. Собранные данные систематизированы и проанализированы с помощью разработанных авторами методик. Для трех наиболее активных поясов Земли – Пацифики, Альпийско-Гималайского и Срединно-Атлантического – установлены новые, отвечающие первому типу ротационных волн, закономерности пространственно-временного распределения сейсмической и вулканической активности. Подтверждена волновая природа их миграции. Полученные в работе данные в совокупности с данными о скоростях движения границ тектонических плит предлагается использовать в качестве нового подхода к решению задач геодинамики. В основе такого подхода заложена идея единства сейсмического, вулканического и тектонического процессов, протекающих в блоковой геосреде и взаимодействующих между собой посредством ротационных волн с симметричным тензором напряжений. Полученные авторами данные позволяют предположить, что при таком взаимодействии сохраняется геодинамическая величина, механическим аналогом которой является импульс. Показано, что процесс волновой миграции геодинамической активности должен описываться в рамках моделей с сильно нелинейными уравнениями движения.

Ключевые слова: миграция, волны, ротация, сейсмичность, вулканизм, геодинамика, закон сохранения, реидность.

1.INTRODUCTION

One of the first important specific features of seismicity, which researchers noted much time ago, is periodicity, i.e. repeatability of the strongest earthquakes in one and the same location at specific time intervals [*Davison, 1936; Ambraseys, 1970*]. Development of instrumental seismology, completion of the global network of seismic stations, introduction of the concept of earthquake magnitude, *M* for instrumental seismological observations [*Richter, 1935; Gutenberg, 1945*], and consolidation of data in global and regional earthquake catalogues on the basis of this concept [*Gutenberg, Richter, 1954; Duda, 1965; Rothe, 1969*] ensured a fairly complete description of the geography of planetary seismicity. As a result, the concept of seismic belts was introduced [*Morgan, 1968; Isaks, 1968*]; it states that seismic belts are stretching along the entire surface of the planet for many thousands of kilometers. Another important scientific result is the theory of seismic gaps [*Fedotov, 1966; Kelleher, 1973; Mogi, 1968b*], which is very productive in forecasting of strong earthquakes [*Fedotov, 1972; Proceedings…, 1978; Sykes, 1971*].

Migration as a property of seismicity was revealed in the first seismic activity maps. On a plane with coordinates (Distance along the belt, *l* / Time, *t*), earthquake foci are located within a straight line, which slope ($dl/dt=V$) determines velocity of migration of the earthquake foci, *V*. The first description of migration of foci of the strongest earthquakes ($M{\approx}8$) was published in the late 1950s by C. Richter [*Richter, 1958*] who reviewed the earthquakes that occurred along the Anatolian fault in Turkey. In the late 1960s, K. Mogi reviewed migration of earthquakes of similar magnitudes along the entire Pacific margin and the eastern termination of the Alpine-Himalayan belt [*Mogi, 1968a*]. In both cases, earthquake migration velocities along the seismic zones were similar and amounted to $V{\approx}200(170 – 230)$ km/year. It was also noted that almost all the foci of the earthquakes of the magnitude range under study were lined up in migration chains. In other words, the phenomenon of earthquake foci migration of the strongest earthquakes was so obvious that it *did not require any proof.*

In the early 1960s, the phenomenon of migration in all regions of the Earth was revealed by G.P. Tamrazyan, S. Duda and many other researchers who reviewed strong ($M{\geq}5$) foreshocks and aftershocks in the foci of individual earthquakes [*Duda, 1963*]. Migration velocities *V* of these events ranged from 10 to 1000 km/year. In 1961, R.Z. Tarakanov and S. Duda [*Duda, 1963; Duda, Bath, 1963*] revealed oscillations of strong aftershocks at the edges of foci of the Kamchatka (1952, *M=9.0*) and Chile (1960, *M=9.5*) earthquakes, both of a length of almost 1000 km; a term of 'boundary seismicity' was introduced later on to describe this phenomenon. In the early 1970s, with development of electronic earthquake catalogues, V.I. Keilis-Borok, A.G. Prozorov, E. Vilkovich, M.G. Shnirman and others proved the phenomenon of migration of foci

of strong earthquakes ($M{\geq}6$) (see also [*Kasahara, 1979; Tadocoro, 2000*]). In 1970, H. Kanamori recorded migration manifested by elastic impulses in the laboratory studies of rock samples [*Kanamori, 1970*]; similar experiments have been repeated many times by other researchers.

In 1975, S.A. Guberman published his concept of the wave nature of earthquakes migration and introduced the notion of effect of *D*-waves. It was then convincingly shown by research results based on numerous actual data that the effect of earthquakes migration is a part of a global phenomenon demonstrating that earthquakes can make clusters in time and space and can be grouped by values of elastic energy released in foci. Relationships between seismic activity and a number of geophysical processes were established. Based on mechanical models [*Elsasser, 1969; Savage, 1971; Nikolaevsky, 1996*], it became possible to reveal that seismicity is associated with movements of tectonic plates, and thus the tectonic nature of earthquake migration waves became apparent. Now the established earthquake foci patterns are successfully applied for prediction of earthquakes. It seemed that the phenomenon of earthquakes migration took its strong position in the Earth sciences and was uniquely associated with the concept of tectonic waves.

The history of evolution of ideas about earthquakes migration and extensive bibliography are available in detailed reviews [*Bykov, 2005; Vikulin, 2003*]. All the published (by 2003) data on earthquakes migration velocities and slow movements of the Earth's crust are consolidated in [*Vikulin, 2003*]. An important conclusion of the given phase of researches was stated by V.G. Bykov [*Bykov, 2005*]: "It has been long accepted that seismic activity is migrating, yet the nature of such migration is still unclear".

Despite the fact that studies of wave earthquake migration, which seemed so promising for both theory and practice, were intensive in the 1960–1970, this field of research failed to gain adequate progress in the 1980-1990's and beyond. Possible causes are described in [*Vikulin, 2011, p. 376*]. Firstly, the earthquakes migration is characterized by small velocities that are smaller than velocities of seismic waves by a factor of 3 to 5 (and more); wave motion equations with symmetric stress tensor are not able to provide an explanation of the nature of such waves, even if appropriate non-linearities are included in the equations. Secondly, all the models applied to explain the wave nature of tectonic waves (and earthquake migration as well) [*Schallamach, 1971; Comninou, 1977; Elsasser, 1969; Savage, 1971; Gershenzon, 2009*] are based on highly nonlinear equations of movement (such as sine-Gordon, Schrodinger and other equations). As a matter of fact, such mathematical equations are based on the concept of asymmetric stress tensor. Even the mathematical rigor of such models and their ability to describe a large number of tectonic and geophysical phenomena do not allow us to recognize these equations as physical models, because neither moment elastic modules included in the models

nor velocities corresponding to such modules have been experimentally determined yet. Besides, these models are determined by quite 'vague' values of their constituent parameters of viscosity and elastic moduli of geomedium and sizes of layers of the crust and lithosphere, which are always effective and specified up to several orders of value in the best case.

Under the concept of *block* geomedium, the analysis of seismicity of the Earth's most active Pacific zone highlighted ways to solving the problem of earthquake migration waves and establishing a relationship between earthquake migration, tectonic and seismic waves [*Vikulin, 2008, 2010*]. Independent studies conducted by different researchers yielded over 50 migration velocities of the Pacific earthquakes with different magnitudes on the plane with the coordinates of 'energy (earthquake magnitude *M*) – velocity (the logarithm of velocity Lg*V*)'; from this database, two types of migration are clearly distinguishable as they are represented by two compact fields of points. Field (*1*) is global; it stretches along the Pacific margin and has lower velocities. Field (*2*) is local; it includes fore-aftershocks in earthquake foci with higher velocities. 'Tilts' of the two fields are different:

$$M_1 \approx 2LgV_1, \quad M_2 \approx 2LgV_2.$$

A margin between the two fields is an extreme value of global migration velocity:

$$V_{1,max} = 1\text{-}10 \text{ sm/s}$$

[*Vikulin, 2010*]. In the rotational model with a symmetric stress tensor, this extreme value can be interpreted as velocity:

$$c_0 \approx \left(\Omega R_0 \sqrt{G/\rho}\right)^{1/2} \approx \left(V_R V_S\right)^{1/2} \sim V_{1,max} \,,$$

where Ω – angular velocity of the Earth's rotation around its axis; ρ, G – density and shear modulus of the Earth; R_0 – typical size of a block of the crust/ lithosphere; V_R and V_S – centrifugal and shear seismic velocities. The velocity yielded from the above equation is typical of block rotating media, including geomedium, in the same way as elastic longitudinal and transverse waves is typical for 'normal' solids [*Vikulin, 2008*]. The extreme value of local migration velocity of earthquakes foci fore-aftershocks in the rotational model is the speed of elastic seismic waves 1 – 10 km/s [*Vikulin, 2010*]. According to the classification [*Bykov, 2005*], global and local waves of earthquake foci migration correspond to slow and fast tectonic waves.

Thus, the analysis of earthquakes migration processes within the Pacific margin allowed us to distinguish between two types of rotational velocities controlling interactions between the earthquake foci in conditions of the planet's rotation around its axis [*Vikulin, 2008, 2010*]. The first

type (with the limiting value of velocity, c_0) is responsible for long-range mechanism of interaction between blocks within the entire Pacific margin, and the second type (with the limiting value of seismic velocities) is responsible for the short range of foreshocks and aftershocks within foci of individual earthquakes [*Vikulin et al., 2011*]. Rheid properties of the geomedium can be explained by rotary-wave mechanism, without involvement of mechanisms of dislocation creep, diffusion creep, structural superfluidity and other mechanism that are well-known in geodynamics [*Vikulin, 2011, p. 384 – 394*]. This means that superplastic deformation of the geomedium, including the vortex geological structures [*Lee, 1928; Xie Xin-sheng, 2004; Vikulin, Tveritinova, 2007*], can be viewed as 'the flow of solid media' [*Corey, 1954; Leonov, 2008*].

Besides the above-described 'longitudinal' earthquake migration *along* the seismic belt, earthquake migration across to the belt was revealed in some parts of the Pacific margin (Japan, Kamchatka and others), based on the data available in the earthquake catalogues covering significant time periods [*Vilkovich, Shnirman, 1982*]; it is termed 'lateral' migration [*Vikulin, 2011, p. 57–69*]. It should be noted that upon establishment of numerous geodetic polygons with quite dense networks of measuring gauges, it was convincingly concluded that strain waves propagate both along and between faults [*Kuzmin, 2009*].

Migration trajectories of foreshocks and aftershocks within foci of strong earthquakes are highly complex [*Vikulin, 2011, p. 109 – 118*]; they often degenerate into oscillation, i.e. alternating increase of activity at different edges of the foci. In foci of the strongest Aleutian earthquakes of 1957, 1964 and 1965 (*M≈9*), which stretched along the latitude, migration of aftershocks from east to west is faster than migration from west to east, and the velocity difference is determined by the Doppler effect associated with the Earth's rotation around its axis. In the areas of the strong Chile (1960) and Sumatra (2004) earthquakes (*M>9*), which stretched along the meridian, aftershocks migrate with the same velocity both from north to south and from south to north [*Vikulin, 2011, p. 109-118*]. These data on migration of foreshocks and aftershocks of strong earthquakes provide the direct *physical* evidence of *wave nature of earthquakes migration* and, in particular, explain the Chandler wobble of the planet pole [*Vikulin, 2002; Vikulin, 2011, p. 244–258*].

The detailed study of regularities of space-time distribution of earthquakes, as exemplified by the most active seismic zone of the planet, allowed interpreting earthquakes migration at the qualitatively new level as a *wave process* and to quantitatively relate it to seismic and tectonic waves [*Vikulin et al., 2010*].

The available data show that volcanic activity (well as seismic activity) events tends to reoccur [*Gushchenko, 1985*], i.e. to occur rhythmically [*Ehrlich, Melekestsev, 1974; Civetta, 1970; Gilluly, 1973; Schofield, 1970*]) and to migrate [*Leonov, 1991; Sauers, 1986; Berg, 1974; Kenneth, 1986; Lonsdale, 1988*], and they can be grouped

by locations with respect to latitudes and longitudes [*Gushchenko, 1983; Fedorov, 2002*] and size [*Golitsyn, 2003; Tokarev, 1987; Hedervari, 1963; Tsuya, 1955*]. Actual data are available which give direct evidence that catastrophic seismic and volcanism events are closely related [*Melekestsev, 2005; Bolt, 1977; Khain, 2008*]. With reference to all the available data, the aim of this research project is to study the processes of 'longitudinal' migration of earthquakes foci and volcanic eruptions along the most active zones of the planet, including the Pacific margin, the Alpine-Himalayan Belt and the Mid-Atlantic Ridge, and to review such processes as interrelated phenomena.

2. SOURCE DATABASE

Data from the world catalogues of earthquakes and volcanic eruptions are consolidated in the special-purpose database in the unified format briefly described in [*Vikulin et al., 2010*]. The database is regularly populated with new data. It includes the following parameters of seismic and volcanic events: date (year, month, day), time (hour, minute, second), coordinates of earthquakes/ volcanoes (longitude and latitude in degree fractions), and depth (it is accepted as zero for volcanic eruptions). The energy characteristics of earthquakes are magnitudes, M, and of eruptions – values W, where $W = 1, 2, ..., 5, ..., 7$ correspond to ejection volumes $10^{-(4-5)}$, 10^{-3}, ..., 1, ..., 10^2 km³. The earthquakes catalogue contains information about 12 725 events that occurred over the last 4.1 thousand years and includes all known data on earthquakes in the period from 2150 BC to 1899, and data on the strongest earthquakes ($M{\geq}6$) in the period from 1900 to 2010. The catalogue of eruptions includes data on 627 volcanoes of the planet, which cover 6 850 eruptions in total through the past 12 thousand year, i.e. from 9650 BC to 2010.

Based on the data from the catalogues, recurrence curves of earthquakes, Lg$N=b{\cdot}M+a$, and volcanic eruptions, Lg$N=B{\cdot}W+A$, are constructed (Figure 1) (N – number of events, value M and W; b and B – slope angles of frequency; a and A – constants, numerically equal to normalized values of seismic and volcanic activity). Slope angles of recurrence curves for different regions of the planet are listed in Table 1 that shows that seismic processes (events of $M{\geq}6$) in areas with different geodynamic settings are characterized by different angles of the recurrence curves. Indeed, for the areas of compression within the margin of the Pacific Ocean and the Alpine-Himalayan belt, the slope angles are similar and amount to $b=-(0.7{\div}0.8){\pm}0.1$, while for the areas of spreading within the Mid-Atlantic ridge, the slope angle is significantly smaller, $b=-1.2{\pm}0.1$. For the planet, an average slope angle of the earthquake recurrence curve is $b=-0.9{\pm}0.3$.

In the representative range of $W{\geq}2$, the slope angles of the curves showing recurrence of volcanic eruptions in different parts of the world differ insignificantly in terms of statistics. In general, for all the regions and individual volcanoes with numerous eruptions (no less than 50), the slope angle can be accepted as $B=-0.5{\pm}0.1$. Considering the curves showing recurrence of volcanic eruptions in all the three zones under study, it seems that the slope angles are constant due to uniformity of geodynamic conditions within the zones that, per se, are the areas of spreading.

The data obtained in this study confirm the conclusion [*Tokarev, 1991; Golitsyn, 2003; Hedervari, 1963; Tsuya, 1955*] about the existence of the volcanic eruptions recurrence law, which actually suggests that volcanic eruptions can be grouped by size, and thus parameter W, as well as earthquake magnitude, M can be considered as energy characteristics of individual eruptions, groups of eruptions, and the volcanic process in general.

Table 1. Slope angles of curves showing reoccurrence of earthquakes (b) and volcanic eruptions (B) in geodynamically active regions

Region	Earthquakes				Eruptions			
	$M_{min} \div M_{max}$	ΔT, years	N	b	$W_{min} \div W_{max}$	ΔT, years	N	B
Worldwide	6 ÷ 9.5	4 160	10 495	-0.9±0.3	2 ÷ 7	11 658	6 850	0.52±0.05
Margin of the Pacific ocean	6 ÷ 9.5	1 362	8 527	-0.8±0.1	2 ÷ 7	11 658	5 877	0.53±0.05
Kamchatka Peninsula	6 ÷ 8.7	273	464	-0.8±0.2	2 ÷ 7	10 058	536	0.48±0.06
Bezymianny volcano, Kamchatka Peninsula					2 ÷ 5	2 460	53	0.38±0.13
Alpine-Himalayan region	7 ÷ 9	4 160	435	-0.7±0.1	2 ÷ 7	10 490	1 600	0.57±0.05
Raung volcano, Java island					2 ÷ 5	422	65	0.55±0.09
Etna volcano, Italy					2 ÷ 5	3 508	186	0.63±0.15
Mid-Atlantic Ridge	6 ÷ 7.6	100	124	-1.2±0.1	2 ÷ 6	10 920	311	0.42±0.09
Laki volcano, Iceland					2 ÷ 6	10 234	63	0.34±0.12

Note. $M_{min} – M_{max}$ ($W_{min} – W_{max}$) – minimum/maximum values of M (W); ΔT – timelines in the catalogues; N – number of events in the catalogues.

3. RESEARCH METHOD

Seismic and volcanic events, considered in the aggregate, have a very distinctive feature - they are scattered along fairly narrow (Λ = 100 – 200 km) long zones (which maximum lengths, L_{max} amount to several dozens of thousands of kilometers); such zones border the entire planet. In studies of spatial and temporal distributions of events, such a configuraion of the zones ($L_{max} \gg \Lambda$) allows using two coordinates instead of three coordinates (latitude, longitude, and time) of the plane with axes 'distance along the belt length l ($0 \leq l \leq L_{max}$) – time t ($0 \leq t \leq T_{max}$)', where $T_{ea,er,max}$ – maximum duration catalogs of earthquakes (*ea*) and volcanic eruptions (*er*).

In this study, the following method is used for conversion of geographical coordinates of the events to distances along line l. The catalogued data on geographical longitudes and latitudes is consolidated into sets of events (with new coordinates, l), and the sets of events are referred to when studying migration of the events in 'space ($0 \leq l \leq L_{max}$) – time ($0 \leq t \leq T_{max}$)', which is revealed by reconstructing sequential chains of events , i.e. migration chains. The three most active zones of the planet - the Pacific margin, Alpine-Himalayan, and the Mid-Atlantic zones - are studied. Locations of earthquakes epicentres, volcanoes and coordinate lines, l, are shown in Figure 2.

Coordinate lines, l, along which migration of seismic and volcanic activity is studied, are constructed by interpolating the systems of nodal points. Integrated Tsunami Database for the World Ocean (WinITDB) software [*Babailov, Beisel, Gusev et al., 2008*] is applied to produce arrays of nodal point and to represent the areas under study in maps showing earthquake foci and/ or volcanoes. Sets of the nodal points are determined for the most active areas (with the largest clusters of events), and thus they typically follow the junction lines of tectonic plates. Geographic coordinates are determined for all the points in the sets.
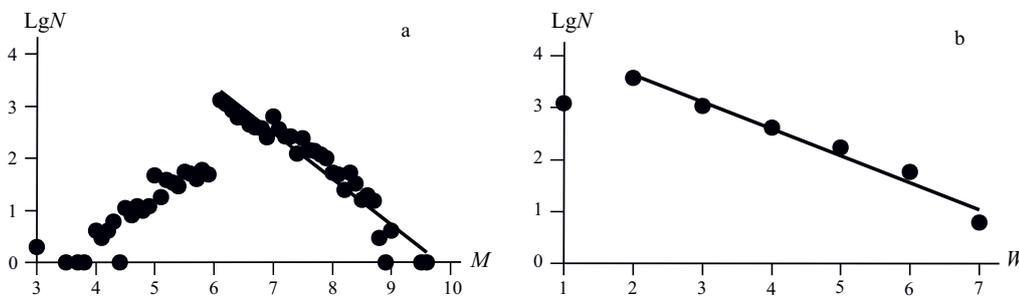

Fig.1. Earthquake (*a*) and volcanic eruption (*b*) recurrence curves. *N* – number of earthquakes and volcanic eruptions.
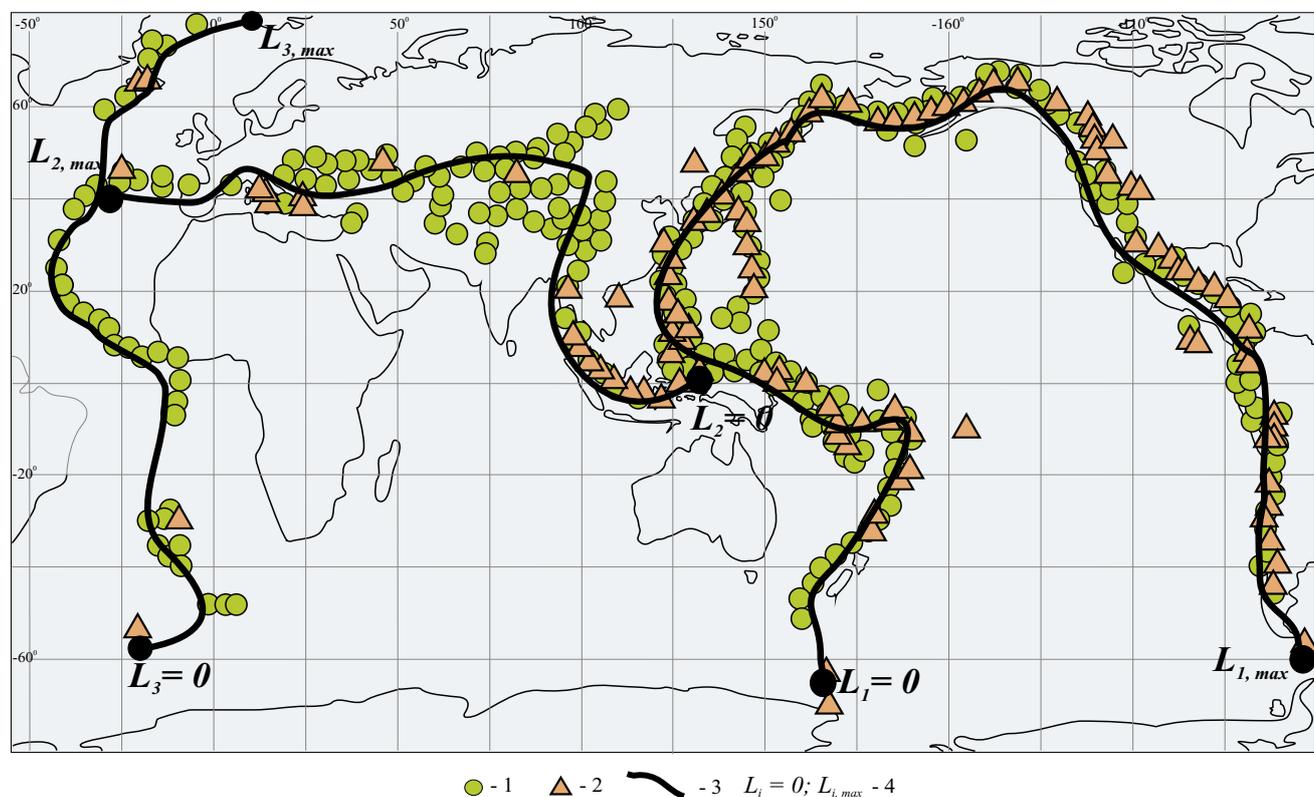

Fig. 2. Active zones of the planet [*Vikulin, et al., 2011*].
1 – earthquake foci; *2* – volcanoes with eruptions; *3* – lines along the axes of the belts in reference to which coordinates *l* of earthquakes and volcanoes are calculated; *4* – terminations of zones ($L_i = 0$; $L_{i, max}$) (*i* = 1 – the Pacific margin; *i* = 2 – Alpine-Himalayan belt; *i* = 3 – Mid-Atlantic Ridge).

Coordinate lines, l are constructed along the Pacific margin (with reference to 59 points), Alpine-Himalayan Belt (39 points), and the Mid-Atlantic Ridge (33 points). For each line, a parametric equation of the interpolating curve is obtained:

$$\begin{cases} \theta = \theta(\tau) \\ \lambda = \lambda(\tau) \end{cases} \tau \in [0; N-1] \quad,$$

where geographic latitude, $\theta(\tau)$ and longitude, $\lambda(\tau)$ are cubic twice differentiable splines; N – number of points on the line. Distances along the Earth's surface from initial point ($\tau = 0$) to point with current coordinates of $\theta(\tau)$, $\lambda(\tau)$ are calculated as follows:

$$l = R_{Earth} \int_0^\tau \sqrt{\left(\frac{d\theta}{ds}\right)^2 + \cos^2\theta(s)\left(\frac{d\lambda}{ds}\right)^2}\, ds \ , \quad (1)$$

where latitude, θ and longitude, λ are given in radians; R_{Earth} – radius of the Earth; $0 \leq l \leq L_{i,max}$.

Lengths of the three most active belts of the Earth are determined as follows (Figure 2): the Pacific margin from Buckle Island Volcano (Antarctica) $L_1=0$ to Desepson Volcano (South Shetland Islands) – $L_{1,max}=45\,000$ km; the Alpine-Himalayan belt from Timor Island (Indonesia) $L_2=0$ to the Azores – $L_{2,max}=20\,500$ km; the Mid-Atlantic Ridge from South Sandwich Islands (South Atlantic) $L_3=0$ to Iceland Island (North Atlantic) – $L_{3,max}=18\,600$ km.

The algorithm for selection of migration chains of seismic and volcanic events within each zone is as follows: for each i-th event in catalog with time t_i and coordinate l_i, an $i+1$-th event is selected so that its time and coordinate can satisfy the condition: $t_{i+1} \geq t_i$, $l_{i+1} \geq l_i$. Migration chains are constructed for different energy ranges, $M \geq M_0$ and $W \geq W_0$, in which the boundary values are widely variable: $6 \leq M_0 \leq 9$, $1 \leq W_0 \leq 6$. For each migration chain, the following parameters are determined: number of events, duration (time interval between the first and last events), length (difference of l coordinates between the first and last events), and migration velocity (calculated from all the events by the least-squares method).

4. EXAMPLES OF CHAINS OF MIGRATING EVENTS

The strongest earthquakes ($M \geq 8$) and volcanic eruptions ($W \geq 6$) are reviewed below. The available catalogues provide long-term coverage of such events, and thus comprehensive information can be obtained about cluster spacing of the chains of migrating events.

Figure 3 shows four consecutive (IX, X, XI and XII) chains of the Pacific earthquakes foci ($M \geq 8$), which occurred in the 18th – 21st centuries within the Pacific Ocean margin ($L_{1,max} = 45\,000$ km) (see Figure 2). As shown in Table 2, in total 23 chains are determined. Every chain shown in Figure 5 is sufficiently representative as it contains from 7 to 10 events. Considering average chain parameters: duration $\Delta T = 150 \pm 80$ years; length $\Delta L = 26.5$

$\pm$ 3.4 ($L_{max}=38$) thousand miles, and migration velocity $V = 260 \pm 160$ km/year, which are consistent with the overall data (see Table 2), it is noted that these chains overlap and almost completely cover the Pacific Ocean margin.

Five chains (I – V) are determined for the mid-Atlantic earthquakes ($M \geq 7$) that occurred in the 20th century (see Table 2). All the chains overlap and cover the entire zone too (Figure 4). However, the chains themselves tend to 'migrate' to $L_3 = 0$ (see Figure 2).

Eight consecutive chains (I - VIII, out of 10 chains determined, see Table 2) of sufficiently strong volcanic eruptions ($W \geq 6$) are determined within the Pacific margin from the available data covering the past 11 thousand years. The first two chains (I and II) overlap and cover the major part ($\Delta L = 22\,000$-$25\,000$ km; $\Delta T = 5.6$-9.4 thousand years; $V = 2.3$-3.8 km/year) of the Pacific margin. Chains III, IV, V and VI cover mainly the northern parts ($\Delta L = 7\,600$-$16\,000$ km; $\Delta T = 4.8$-8.4 thousand years; $V = 1.2$-2.5 km/year). Chains VII and VIII cover the eastern (VII) and south-eastern (VIII) parts ($\Delta L = 8\,800$-$14\,000$ km; $\Delta T = 3.0$-3.4 thousand years; $V = 2.4$-2.5 km/year).

Figures 3 and 5 show the world's longest belt, the Pacific margin ($L_{3,max} = 45\,000$ km, see Figure 2) which database includes information about seismic events for 1400 years and volcanic eruptions for 11 thousand years. The longest seismic and volcanic chains overlap and cover the major part of the Pacific margin. As shown in Figure 5, the shorter-than-maximum volcanic chains tend to be smaller in terms of both length and time. However, no significant changes in migration velocity of volcanic eruptions are revealed. Each event included in the chain is then excluded from any further reconstructions. This may explain changes in lengths and durations of the last chains and also a reason of the trend of 'migration' to $L_{1,3} = 0$, which can thus be considered as consequences of 'knocking out' of the events by the preceding chains from the catalogue of strong events, as well as longer periods of recurrence and limited lengths of the zones.

Cluster spacing of migration of chains of weaker events has not been studied in detail. Weak seismic ($M<8$) and volcanic ($W<6$) events are quite frequent, and weaker events occur more often, as shown by the recurrence curves (see Figure 1). With decreasing energy characteristics of the events, the number of migration chains increases, while timelines and lengths of the chains do not change significantly, as described below (Table 2). It is assumed that the majority of the chains comprising weak events can compose a quite 'uniformly' dense cover over the entire zone, as they demonstrate a major overlap with each other.

5. MIGRATION AND GEODYNAMIC SETTINGS

The most typical examples of the migration chains are shown in Figure 6, and their parameters of seismic and volcanic activity are given Table 2, which also includes the data from our earlier studies [*Akmanova, Osipova, 2007; Vikulin, 2003, 2010; Vikulin et al., 2010*].
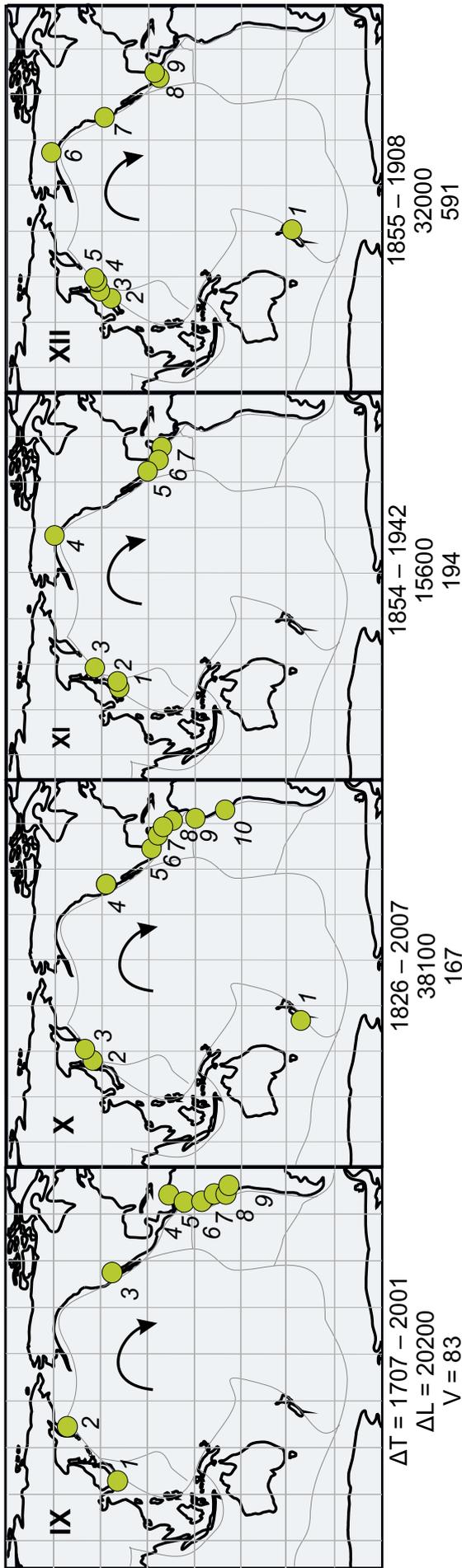
Fig. 3. Locations of four sequential chains of foci of the Pacific earthquakes ($M \geq 8$) that occurred in the period from 1707 to 2007.
I = IX, X, XI and XII – serial number of a chain; $i = 1 - 10$ – serial number of events in a chain; ΔT [year] = $t_2 - t_1$ – chain timeline, where t_1 and t_2 – time of the first and the last event in the chain; ΔL [km] = $l_2 - l_1$ – chain length as a difference between coordinates of the last (l_2) and the first (l_1) events in the chain; arrows show directions of migration in chains of events.
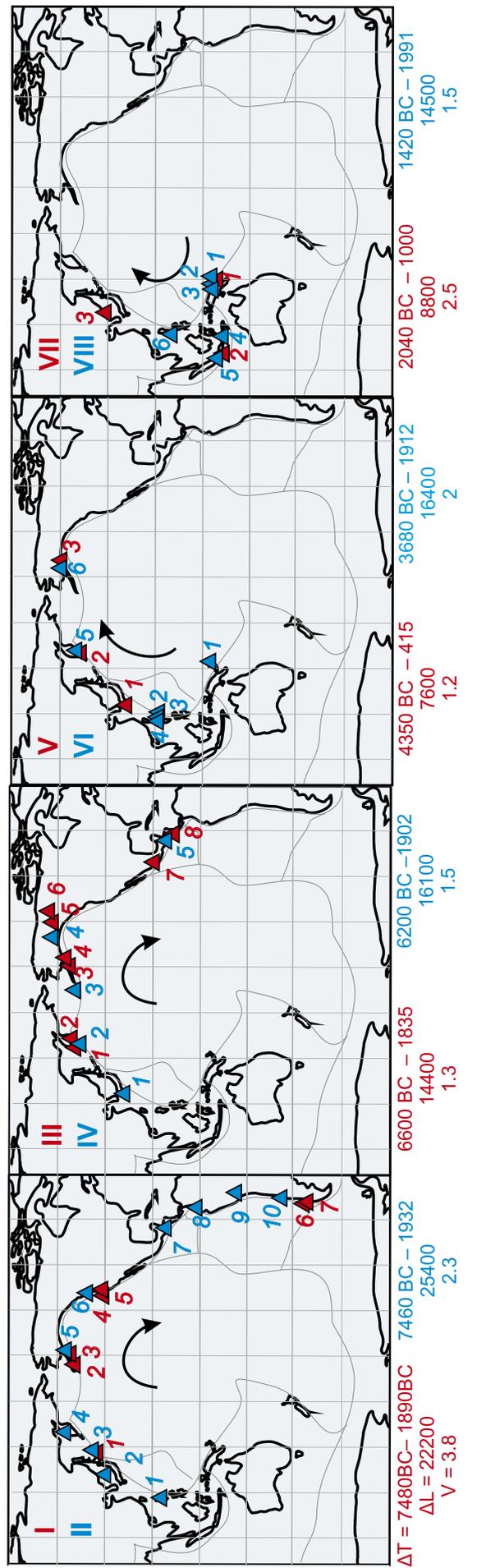

Fig. 5. Locations of eight sequential chains of volcanic eruptions ($W \geq 6$) that occurred within the Pacific margin in the period from 7480 BC to 1991. See the legend in Figure 3.
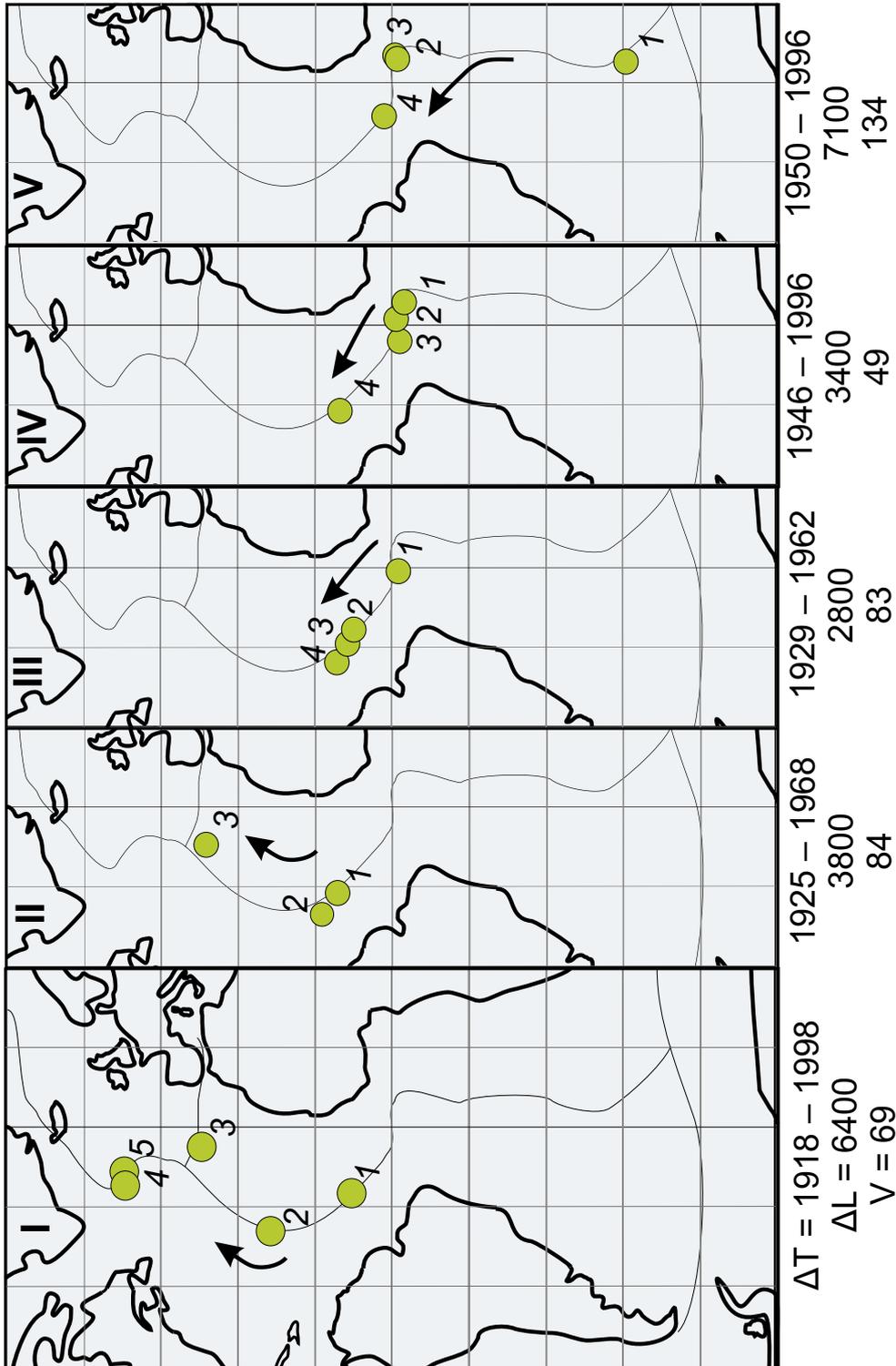
Fig. 4. Locations of five chains of foci of the mid-Atlantic earthquakes (*M* ≥ 7) that occurred in the 20th century. See the legend in Figure 3.

Table 2. Parameters of migration chains of earthquakes and volcanic eruptions revealed in the regions under study

Earthquakes					
$M \geq M_0$	k	$N \pm \Delta N$	$T \pm \Delta T$	$L \pm \Delta L$	$V \pm \Delta V$
The Pacific margin					
M≥6	177	35±11	110±100	18 900±6 600	150±60
M≥6.5	113	24±8	140±130	18 800±6 500	190±40
M≥7	85	18±6	170±150	17 200±7 600	190±90
M≥7.5	52	12±3	190±170	17 700±6 600	240±90
M≥8	23	8±2	260±240	19 600±4 900	400±230
M≥8.5	7	4±1	320±370	13 300±7 800	640±500
The Alpine-Himalayan seismic belt					
M≥7	30	10±3	550±720	6 700±2 300	280±290
M≥7.2	24	9±2	520±660	7 100±2 100	160±70
M≥7.5	20	7±2	450±530	7 000±2 400	370±150
M≥7.7	15	5±1	100±90	6 800±2 100	330±160
M≥8	4	4±1	110±60	3 800±2 200	590±280
The Mid-Atlantic ridge					
M≥6	19	6±2	40±30	5 900±2 500	340±250
M≥6.2	14	6±2	40±30	5 900±2 500	160±120
M≥6.5	8	5±1	50±20	5 100±2 600	170±130
M≥6.7	6	5±1	50±10	6 000±2 100	120±70
M≥7	5	4±0.3	50±10	4 700±1 600	90±30
M≥7.2	1	7	80	6 400	90
Volcanic eruptions					
$W \geq W_0$	k	$N \pm \Delta N$	$T \pm \Delta T$	$L \pm \Delta L$	$V \pm \Delta V$
The Pacific margin					
W≥1	110	51±17	2 150±2 790	19 900±8 400	70±50
W≥2	103	45±16	2 280±2 890	19 400±8 900	60±40
W≥3	56	23±9	3 490±3 370	20 300±8 300	60±80
W≥4	34	14±5	4 470±3 390	21 800±7 800	20±20
W≥5	18	9±3	5 010±3 120	22 700±9 700	13±14
W≥6	10	6±2	5 050±2 370	15 400±5 200	3±1
The Alpine-Himalayan seismic belt					
W≥1	43	37±15	1 130±1 420	4 700±3 300	13±7
W≥2	42	31±14	1 150±1 440	4 700±3 300	11±6
W≥3	23	13±6	1 890±2 020	4 300±3 400	9±8
W≥4	10	6±2	2 750±2 860	4 300±3 400	4±3
W≥5	5	4±1	3 390±2 500	4 900±3 600	3±2
The Mid-Atlantic ridge					
W≥1	12	21±12	3 360±2 840	4 200±3 500	2±2
W≥2	12	20±13	3 110±2 770	3 400±2 900	3±4
W≥3	7	16±9	4 260±2 450	6 100±3 300	1±0.5
W≥4	4	14±4	5 620±1 220	6 200±3 100	1±0.7
W≥5	2	5±1	1 690±1 560	2 700±2 100	0.30±0.01

Note. M – earthquake magnitude; W – 'energy' of eruption; M_0 and W_0 – the lowest values of M and W in the database under study; k – number of revealed migration chains in cases that one event is included only in one migration chain; in cases when one and the same event occurs in several chains, the value of k for every such chain is increased roughly by a factor of ten; N – average number of earthquakes and/or volcanic eruptions in a migration chain; T – average timeline of a migration chain (year); L – average length of a migration chain (km); V – average migration velocity of earthquakes and volcanic eruptions of various 'energy' ranks (km/year); ΔN, ΔT, ΔL and ΔV – root-mean-square deviation of N, T, L and V, respectively.

Similar to the data on the Pacific margin, the data in Table 2 and Figure 6 for the Alpine-Himalayan Belt and the Mid-Atlantic Ridge show that migration of seismic and volcanic activity is a typical process that takes place commonly and has wave nature.

Actually, Table 2 seems to be the most comprehensive collection of data on migration of seismic and volcanic activity in the three most active zones of the planet. The tabulated data on each seismic and volcanic belt reviewed in this study show that there are specific changes in migration velocities in proportion to end values M_0 and W_0 of the reviewed sets of events. According to Table 2, relationships between logarithms of migration velocities of seismic and volcanic events, LgV and values M and W for each zone are determined by the least-squares method as follows:

$M = (3.7 \pm 0.6)LgV - 1.6$; $M = (1.5\pm 0.7)LgV + 3.7$;
$M = (-1.9 \pm 0.4)LgV + 10.7$, (2 a, b, c)

$W = (-2.3 \pm 0.3)LgV + 7.2$; $W = (-3.8\pm 1.2)LgV + 6.6$;
$W = (-2.0 \pm 2.1)LgV + 3.6$. (2 d, e, f)

Each of the three seismic (2a-c) and volcanic (2d-f) correlations corresponds to the edge of the Pacific, the Alpine-Himalayan belt and the Mid-Atlantic Ridge. Correlations (2a-f) are shown in Figures 4a-f, respectively. The root-mean-square error in determinations of the slope angles of seismic (2a-c) and volcanic (2d-f) correlations is within the range as follows:

$$\Delta p_{M,W} = 0.3 - 2.1, \Delta p \approx 0.9 ,$$ (3)

where Δp is an average deviation.

Correlation (2a) confirms relationship $M(LgV)$ for the Pacific margin, being of wave nature, which we established earlier. It can thus be logically concluded that all other correlations (2b-f) confirm wave nature of migration of seismic and volcanic activity in all the three zones under study.

Slopes of seismic curves $LgV \approx p_{Mi}M$ for the zones located in different geodynamic settings are significantly different. For the Pacific margin ($i = 1$, (2a)) and the Alpine-Himalayan belt ($i = 2$, (2b)), which are known as
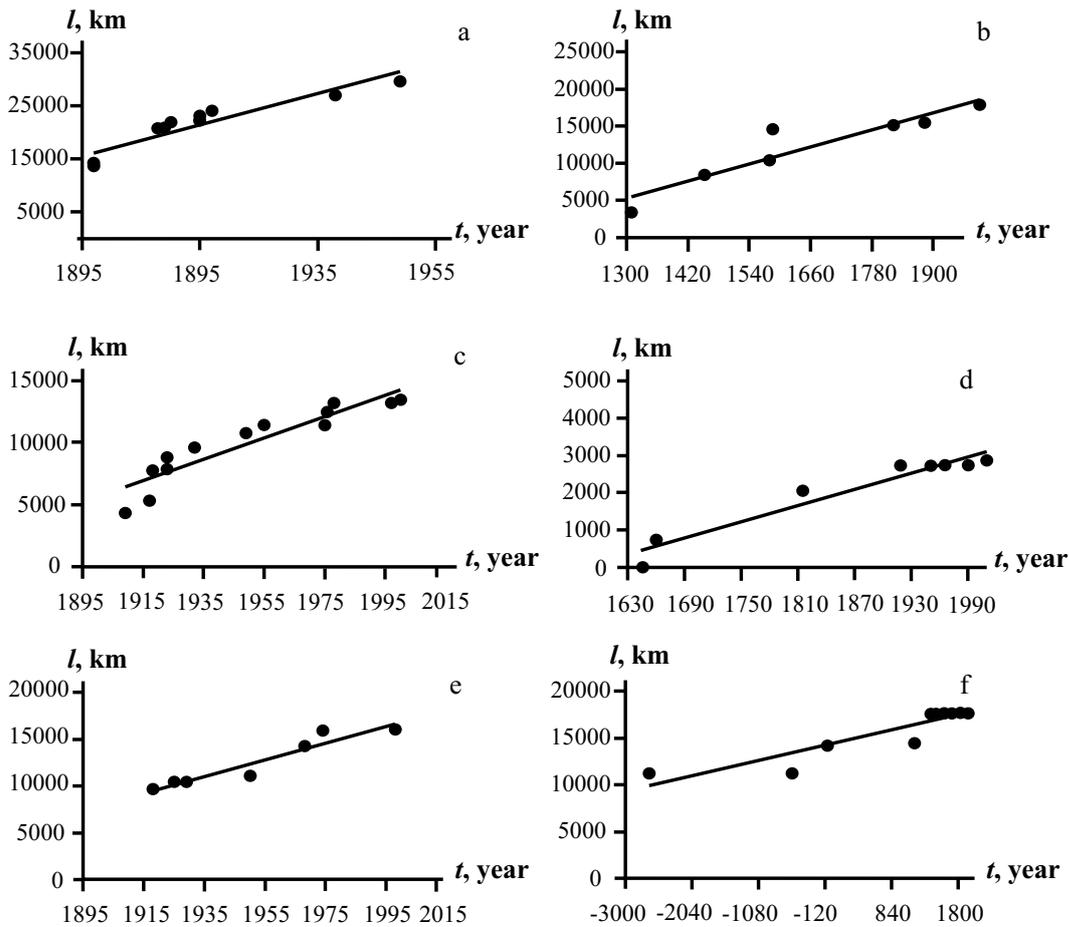

Fig. 6. Examples of migration chains.

a and b − migration chains of earthquake foci ($M \geq 8$) and volcanic eruptions ($W \geq 5$) within the Pacific margin; c and d – migration chains of earthquake foci ($M \geq 7$) and volcanic eruptions ($W \geq 4$) within the Alpine-Himalayan Belt; e and f – migration chains of earthquake foci ($M \geq 7.2$) and volcanic eruptions ($W \geq 4$) within the Mid-Atlantic Ridge.
Migration velocities, V and correlation coefficients of linear chains/regressions R_2 for the chains shown in Figure 6: V = 300; 90; 90; 20; 7; 2 km/year, and R_2 = 0.88; 0.86; 0.86; 0.93; 0.90; 0.84, respectively.

zones of compression, it is established that ratios $p_{M,1,2}>0$ (Figures 7a, b, respectively). For the Mid-Atlantic Ridge (which is known as zone of stretching) ($i = 3$, (2c)), $p_{M,3}<0$ (Figure 7c).

Slopes of volcanic curves $LgV \approx p_{Wi}W$, showing specific features of migration of volcanic eruptions, are negative: $p_{W,i}<0$, ($i = 1, 2, 3$, (2d–f), Figures 7d–f) along all the three zones under study. Such a decrease of migration velocity of volcanic eruptions with increasing values of W seems to be related to tension stresses within all the volcanic belts; the tension stresses are caused by magma penetration from the depth.

The results of this study show that specific features of spatial and temporal patterns of seismic and volcanic activity (a wave migration process as it is), as well as features of 'energy' distribution (variable values of the slope angles of frequency curves) are fairly 'sensitive' to the character of *geodynamic* (seismic and volcanic) movements – compression (subduction)/ stretching (spreading) – in the active zones and their vicinity.

6. DISCUSSION OF RESULTS

For the purpose of this study, the most complete database on earthquakes and volcanic eruptions of the planet for the period of *thousands of years* is systematically consolidated and analysed by the original methods proposed by the authors. It is confirmed that migration of earthquakes and volcanic eruptions along the Pacific, the Alpine-Himalayan and the Mid-Atlantic zones is of wave nature. New regularities of spatial and temporal patterns of seismic and volcanic activity are established as functions of energy characteristics of processes. Being considered *in aggregate*, they clearly suggest a close relationship between seismicity and volcanism, on the one side, and geodynamic settings of the zones, on the other side. On the basis of these

data in combination with information about velocities of movements of tectonic plate boundaries [*Vikulin, Tveritinova, 2008*], a new approach can be developed to solving problems of geodynamics, comprising interrelated seismic, volcanic and tectonic processes [*Vikulin, 2011; Vikulin et al., 2011*]. The correlation between migration velocities and energy characteristics of the process (Equation 2) determines the format of laws of motion describing the process of migration as strongly nonlinear equations.

Currently, the problem is addressed with other approaches based on review and analyses of regional-scale source data. In the Institute of the Earth's Crust SB RAS, tectonophysicists and geologists have been studying faulting in the lithosphere for many years. They proposed a model of the deep structure of faults in Central Asia [*Sherman et al., 1992, 1994*] and completed the following studies:

- Physical modelling of formation of large faults in the lithospheric extension zones, and determination of quantitative characteristics of the deformation process taking place in such zones [*Sherman et al., 2001*];

- Development of the original geodynamic model of space-time development of rift basins of the Baikal region and Transbaikalia [*Lunina et al., 2009*],

- Development of a tectonophysical model of a seismic zone [*Sherman, 2009*], which confirms that faults are activated due to *low deformation waves* of excitation being generated by interplate and interblock movements of the lithosphere [*Sherman, Gorbunova, 2008*] and also occur in zones of slow migration of seismicity (i.e in zones of earthquake clusters which can be considered as the lithosphere blocks) [*Novopashina, 2010; Sherman, 2009; Sherman et al., 2011*].

The concept of the above mentioned tectonophysical model of a seismic zone includes the following: fault-block media, real-time activation of faults due to
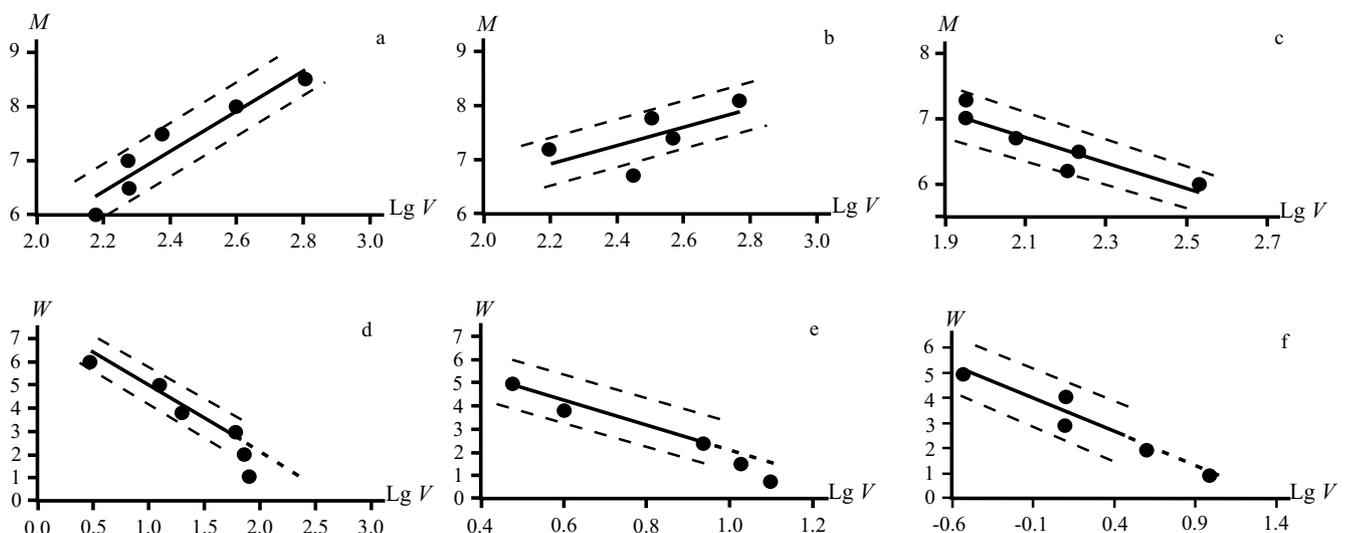

Fig. 7. Migration velocity V of earthquakes (a, b, c) and volcanic eruptions (d, e, f) versus energy characteristics M and W of the events. *a and d* – the Pacific margin; *b and e* – the Alpine-Himalayan belt; *c and f* – the Mid-Atlantic Ridge. Correlation coefficients of linear regressions for curves (*a to f*): $R_2 = 0.90; 0.61; 0.88; 0.96(0.87); 0.93; 0.49(0.88)$.

deformation waves, and seismic events that occur sequentially. According to [*Sherman, 2009*], development of the comprehensive tectonophysical model of the seismic process and its solutions «will pave the direct way to obtaining the knowledge on spatial and temporal patterns of earthquakes and to prediction of earthquakes». However, our research results suggest that this way being 'battled through' in the regional direction [*Sherman et al., 1992, 1994, 2001, 2008, 2011; Sherman, 2009*] may prove to be not so direct.

According to [*Sherman, Gorbunova, 2008*], migration velocities *V* of earthquakes of energy class *K ≥ 12 (M ≥ 4-5)* vary from 1 to 100 km/year, and this conclusion is consistent with the above described correlations (2a, b) for the Pacific margin and Alpine-Himalayan belt, both being subduction zones. However, it contradicts with correlation (2c) for the Mid-Atlantic Ridge that is the zone of spreading. S. Sherman and his colleagues study the region in Central Asia which is a rift, i.e. the zone of spreading. In view of our research results, there is a contradiction between their data on earthquake migration in Central Asia and our data on the zones of spreading. Otherwise, it has to be admitted that either the subject region of Central Asia is not a rift, or their data on earthquakes migration cover only one side of the rift and thus do not refer to the entire rift zone.

Besides, we cannot accept their tectonophysical interpretation of the results obtained for the above mentioned region of Central Asia region. According to [*Sherman, Gorbunova, 2008*], lengths, *l* of faults activated by deformation waves, and lengths, *L* of the deformation waves passing through the faults are typically related as *L≥l*. A question is how can a fault (that does not radiate any waves and only gets activated) 'be aware' of the length of the wave passing through it? The authors answer this question through the statement that the time of fault activation and the earthquake migration velocity are related to the length of the wave passing through the fault.

The studies conducted by S.I. Sherman and his colleagues provide a basis for linking two large zones of faulting in the Baikal rift zone and the Amur region; active fractures are identified, and it is shown that fault activation is manifested through seismicity, which is triggered by specific mechanisms, including slow deformation waves that pay a leading role in this process [*Sherman et al., 2011*]. Anyway, the overall picture of the seismic and geodynamic setting of the entire Baikal-Amur zone, considered as a global intraplate boundary, is still quite vague, 'regional' hypothetically cross-linked only for some separate locations.

Thus, the 'regional' approach to the problem does not yield a complete picture. Moreover, while designing a model, the researchers have to introduce relationships between the parameters and thus to considerably restrict interpretations of the model's consequences at the final stage of research which is critical for geodynamical conclusions.

With a reasonably generalized approach to the problem, it is basically possible to apprehend the challenges of the Earth's sciences and refresh definitions of *geodynamic* problems to be resolved. In this respect, the first results of our study offer principally new options of physical interpretation of the geodynamic correlations and regularities.

According to [*Vikulin, Tveritinova, 2008*], same as the energy of seismic and volcanic processes, the energy of tectonic plate movements, E_T is proportional to movement velocity:

$$LgE_T \approx p_T LgV, \qquad (4)$$

and the factor of proportionality is equal to that in the seismic correlation for the Pacific margin:

$$p_T \approx p_{M1} . \qquad (5)$$

The geodynamic activity of the planet is determined by seismic, volcanic and tectonic processes which are considered cumulatively. The three most active zones of the planet release over 98% of the Earth's seismic and volcanic energy and host nearly all the most hazardous earthquakes and volcanic eruptions. Correlations (4) and (5) published in [*Vikulin, Tveritinova, 2007, 2008*] yield from the analyses of velocities of movements estimated for almost all the most active boundaries of the tectonic plates of the planet. We believe that specific features of the energetics of the geodynamic (seismic + volcanic + tectonic) process should be determined from seismic and volcanic relationships (2a-f), supplemented by similar tectonic relation (5), in which p_T is taken equal to the slope angle specified in the correlation for the seismic Pacific margin (2a).

Of special interest is distribution of values of coefficient *p* in correlations (2a-f) and (5). The sum of slope angles of seismic (2a-c), volcanic (2d-f) and tectonic (5) correlations, taking into account the accuracy of their determinations, is equal to zero:

$$\sum_{i=1}^{3} p_{M,i} + \sum_{i=1}^{3} p_{W,i} + p_T \pm 7\Delta p = -1.1(\pm 6.3) \approx 0 , \quad (6)$$

with approximately equal 'positive' and 'negative' values of the slope angles ($p_+=\{p_{M1,2,T}>0\}$; $p_-=\{p_{W1,2,3,M3}<0\}$, respectively) in absolute magnitude:

$$p_+=+3.6\pm0.6; \; p_-=-2.5\pm1.0; \; |p_+|\approx| \, p_-| . \qquad (7)$$

It seems that splitting of coefficient *p* in two much-the-same sets of values, p_+ and p_- (7), which 'compensate' each other in the sum (6), is non-random.

The set of $p_{M,W,T}$ values describes regularities of *different* processes (*M* – seismic, *W* – volcanic, and *T* – tectonic) taking place in *different* physical and chemical conditions, *different* geodynamic settings, in *separately reviewed*

regions and the planet as a *whole*, and timelines of such processes are *quite extensive*. Notwithstanding such a variety of conditions, the geodynamic process (that can be called 'breathing of the Earth') takes place in such a ways that volcanic, seismic and tectonic movements tend to 'compensate/balance out' each other, as shown in Equation (6). In other words, grouping the values of coefficient p in quite simple sets described by Equations (6) and (7) is essentially typical of conservation laws. It can thus be assumed that the total set of values

$$p=\{p_M, p_W, p_T\}= \{p_+, p_-\} \qquad (8)$$

is actually *conserved geodynamic value p*.

Upon one-to-one splitting of the complete set (8) of seismic (M), volcanic (W) and tectonic (T) values $p = \{p_M, p_W, p_T\}$ in two sets $p=\{p_+, p_-\}$, each corresponding to a specific geodynamic situation (p_+ for subduction, and p_- for spreading), it is possible to state a physically limpid assumption: conserved geodynamic value p depends on the direction of the process and is thus *vector variable*.

According to Equation (2), parameter p is determined as follows:

$$p = \frac{dM}{d(LgV)} = \frac{d(LgE)}{d(LgV)} = \frac{V}{E}\frac{dE}{dV} \quad , \qquad (9)$$

where earthquake magnitude, M and energy, E released in the earthquake focus are related according to the well-known relation: $M{\approx}LgE$. According to [*Landau and Lifshitz, 1973*], value dE / dV is termed as generalized momentum in mechanics.

The values of velocities and magnitudes/energy are highly uncertain, as shown in Table 2. This means that, within the intervals under study, in any sufficiently large neighborhood (ΔM_0, ΔV_0) of the point (V_0, M_0), for example, in the neighborhood of (M_0=7±1, V_0=280±290 km/year), geodynamic value $p{\cdot}E_0 / V_0$ (or value p in case of constant E_0 and V_0) can be interpreted as momentum of the geodynamic system.

In combination with the available data on tectonic plate movements, the new data obtained in this study of regularities of the planetary patterns of earthquake and volcanic eruption provide for determination of a parameter of the geodynamic process, which can be analogous to mechanical momentum. In further research, it may be possible to design *fundamentally new physical models* based on seismic, volcanic and tectonic data in order to describe the geodynamic processes that take place in active zones of the planet.

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