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The investigation of electromagnetic precursors to earthquakes in Armenia

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Abstract
The present work provides a sufficient theoretical substantiation of the anomalous distribution for Very-Low-Frequency (VLF) radio waves which is observed for all radio routes controlled by the National Survey for Seismic Protection (NSSP) of the Republic of Armenia. This event is connected with the ionosphere excitement over the strong seismic event preparation zone under the influence of intensively oscillated VLF electromagnetic waves falling on the ionosphere from the source called an area of uniformly oriented Zones of Separated Charges (ZSC) in the strong seismic preparation zone. ZSC, formed at the interfaces of solid, liquid, and gaseous phases of rocks, acquire identical orientation under the action of increasing elastic strain forces. These strain forces may cause the effect of mutual polarisation of ZSC in the field of their high concentration. As a result, in the strong earthquake preparation zone, the most sensitive to the deformation ZSC, non-linear electromagnetic effects may be observed. One of these effects is the irreversibility of non-stationary electromagnetic processes (INP). It is shown that the INP method developed by Balassanian and Kabilsky (Balassanian, 1990) may prove to be very sensitive to the deformations of geological medium in the earthquake preparation zone.

Key words *Armenia – electromagnetic – precursors – earthquake*

1. Introduction

The geological medium, including seismically active zones, is known to be made up of solid, liquid and gaseous phases. Again it is well known that ZSC (Balassanian, 1990) or double ionic (electric) layers, as they are defined in physical chemistry, are formed at the interfaces of solid and liquid phases of rocks (Doukhin and Shilov, 1972). Proceeding from its individual structure, each ZSC of the geologic medium is characterised by its capacity (*C*), inductance (*L*) and resistance (*R*) and has the following specific features: charges separated both along and across the phase interface (Dukhin, 1972); multiplicity of layers, which are in general up to 1 μm thick (Dukhin, 1972); huge electric capacitance with ε^* complex dielectric permittivity, ranging up to 10^5 at the cost of gigantic low frequency dielectric dispersion effect (Dukhin, 1972); electrostatic field strength featuring values of 10^5-10^8V/cm (breaking for dielectrics) within the ZSC both along and across the phase interface (Dukhin, 1972; Balassanian, 1990).

Prior to strong seismic event preparation, each ZSC in a seismically active zone that is noted for high mobility can be exposed to various local and regional physical forces orienting the ZSCs in different directions. A predominant physical impact – the intensity of elastic strains – appears in a seismically active zone during strong earthquake preparation. The prevailing intensity of elastic strains exerts the

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principle orienting impact over different ZSCs of strong seismic effect preparation zone.

With the increase in deforming elastic strains, in the seismic event preparation zone at least two phenomena should be observed:

– formation of one or several groups of identically oriented ZSCs which grow gradually in the area of identically oriented ZSC that reaches its maximum size by the time of rock rupture, *i.e.* up to a strong earthquake;

– mutual polarisation of ZSC in the zones of ZSC high concentration.

Both phenomena described above can serve as a source of specific electromagnetic anomalies that are often observed during the period of earthquake preparation – disturbance of VLF radio wave propagation, preseismic nonlinear electromagnetic effects.

2. Radio wave precursors to strong earthquakes

Ionosphere phenomena preceding strong seismic events have been repeatedly described and discussed by different researchers (Gokhberg *et al.*, 1987).

It is common that after new experimental data not fitting into the existing theoretical concepts of one or another physical or geophysical process three different points of view can arise targeted to their interpretation:

– the experimental data were obtained incorrectly;

– the observed phenomena are not related to the earthquake preparation process;

– the observed phenomena are related to the earthquake preparation process.

Excluding incorrectness in measuring ionosphere phenomena, since they were observed by different research groups, one principal question remains to be answered – whether the nature of these phenomena is seismogenic or not.

Although Gufeld *et al.* (1992) noted that a stochastic relationship between a certain type of ionosphere disturbances and seismic events (M = 4-7) is established with a confidence level of more than 90% for 1200 earthquakes analysed, the physical nature of the ionosphere disturbances is open to question. Probably this is determined by:

– an unclear mechanism of lithosphere-ionosphere interactions over the seismically active zones;

– a discrepancy between the observed ionosphere phenomena and the mechanical theory of earthquake origination;

– an insufficient number of experimental data obtained independently.

The present work provides new experimental data related to this field and obtained through special investigation carried out in the NSSP to study lithosphere-ionosphere interactions in seismically active zones.

2.1. *The measurement procedure used to study lithosphere-ionosphere interactions over seismically active zones*

Since the first days of its creation, *i.e.* 1991, the NSSP (National Survey of Seismic Protection) has implemented special monitoring of the characteristics of VLF radio wave propagation along the radio routes passing through different seismically active zones of the Earth. In doing so the OMEGA radio navigation system is used as a transmitter, while the Ч7-38 stations installed in the NSSP in Yerevan are the receivers.

The VLF radio wave Ч7-38 receivers register phase shift ($\Delta\varphi$) between the VLF radio wave radiated by the RNS OMEGA and reflected from the ionosphere on the one hand, and standard signal formed by the СЧВ-74 – atomic frequency standard, on the other hand.

The present work provides the data of longstanding observations made along the radio routes uninterruptedly controlled by the NSSP (fig. 1).

– Monrovia (Liberia) - Yerevan, f = 12.0 kHz;

– Reunion Island (France) - Yerevan, f = 12.3 kHz;

– Tsushima Island (Japan) - Yerevan, f = 12.8 kHz;

– Aldra (Norway) - Yerevan, f = 12.1 kHz.

Such selection of radio routes allowed us for the first time:

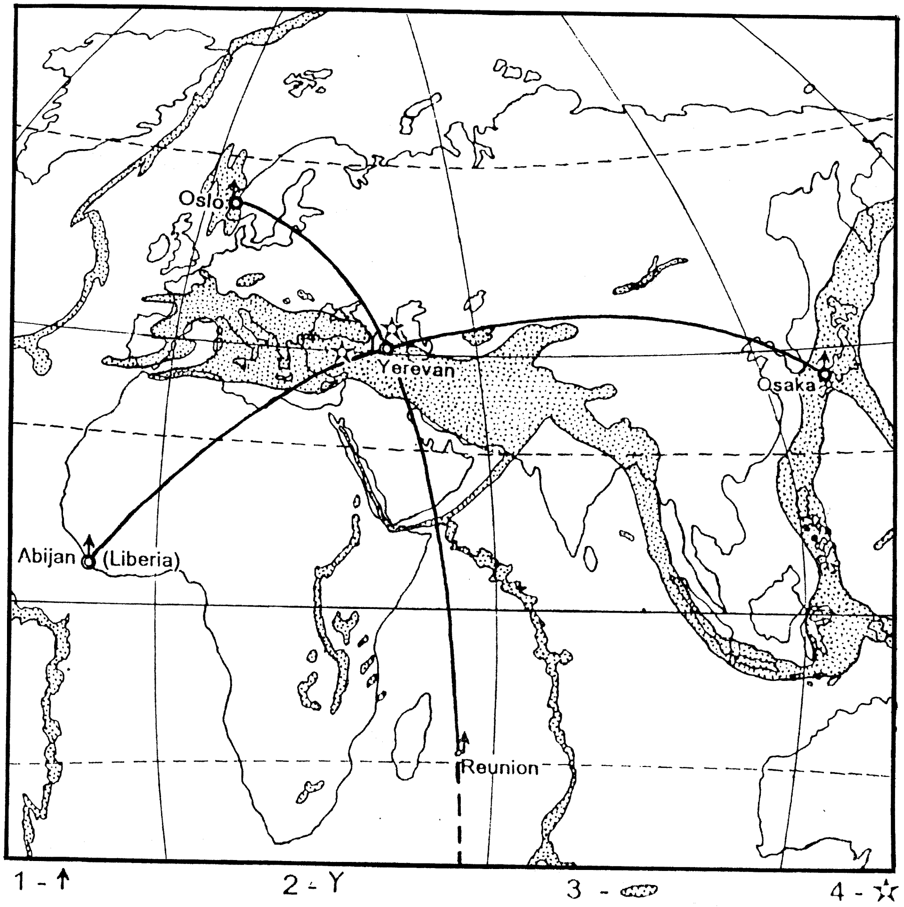

Fig. 1. Scheme of location of the radio routes controlled by the NSSP. 1) The RNS «OMEGA» transmitters; 2) the VLF radio wave receiving station of the NSSP; 3) seismically active zones; 4) epicentres of the Erzincan (Turkey, 1992, $M_S = 6.8$) and Barysakho (Georgia, 1992, $M_S = 6.4$) strong earthquakes.

– to make observations on the investigation of lithosphere-ionosphere interactions through installing the VLF radio wave receivers directly in a seismically active zone;

– to obtain duplicated and controlling information along the four radio routes when the earthquake preparation zone is being formed in the territory of Armenia or adjacent countries, that is, one is situated within the zone controlled by all four radio routes;

– to study the effect of respective location of the receiver, transmitter and earthquake preparation zone on the character of ionosphere disturbances observed during the preparation of seismic events with different intensity and hypocentral depth.

2.2. *Results of the observations*

Figures 2a-d and 3a-d present the results of VLF radio wave propagation observations along the radio routes controlled by the NSSP during the preparation and realisation of Erzin-

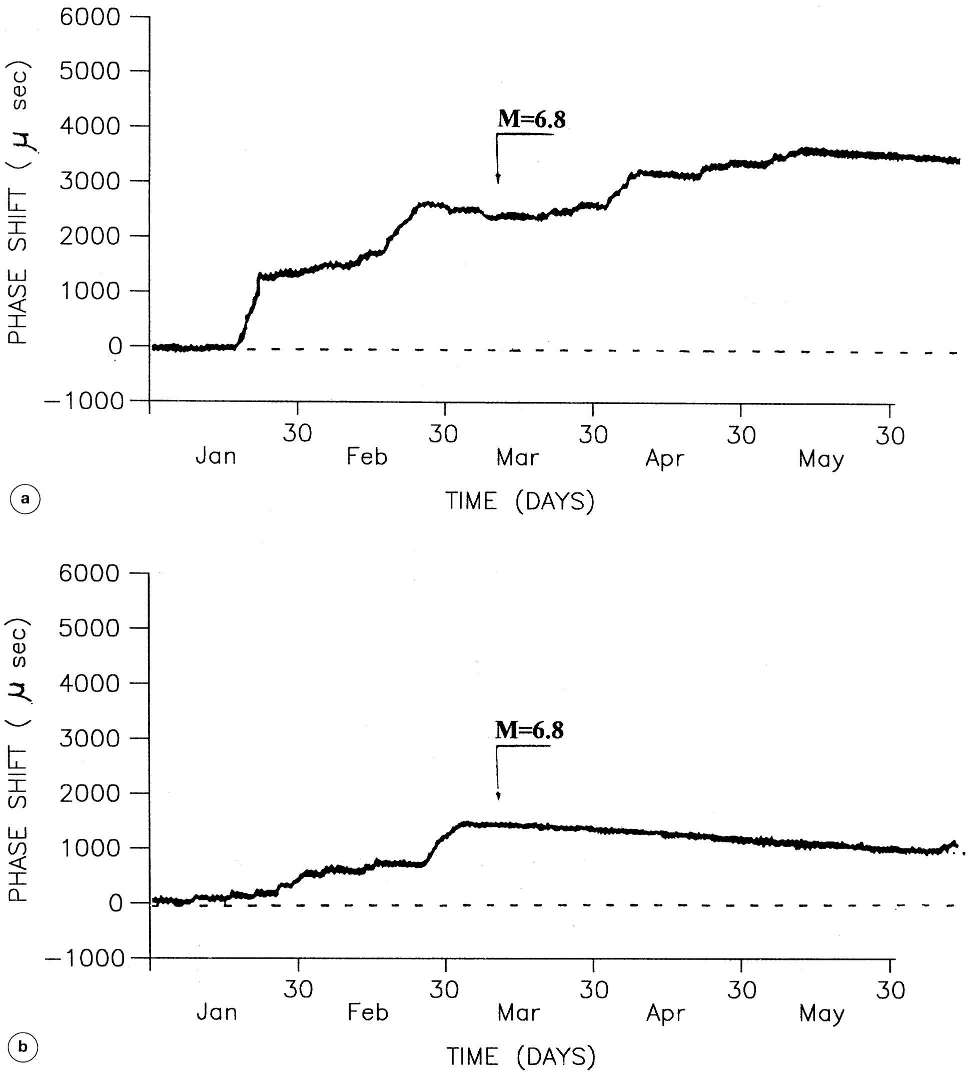

Fig. 2a,b. The effect of prolonged loss of phase cycles along the VLF radio wave routes controlled by the NSSP during the Erzincan earthquake (March 13, 1992, Turkey, $M_S = 6.8$) preparation and realisation. a) The radio wave route Monrovia (Liberia) - Yerevan; b) the radio wave route Reunion Island (France) - Yerevan.

can (March 13, 1992, Turkey, $M_S = 6.8$) and Barysakho (October 23, 1992, Georgia, $M_S = 6.4$) earthquakes.

It is clear from the presented data that the effect of Phase Cycle Prolonged Loss (PCPL) is observed for all the radio routes during the preparation of the mentioned strong earthquakes. The PCPL effect points to the disturbances in the ionosphere above the strong earthquake preparation zone. These disturbances disrupt normal propagation of the VLF radio waves emitted by the RNS OMEGA and,

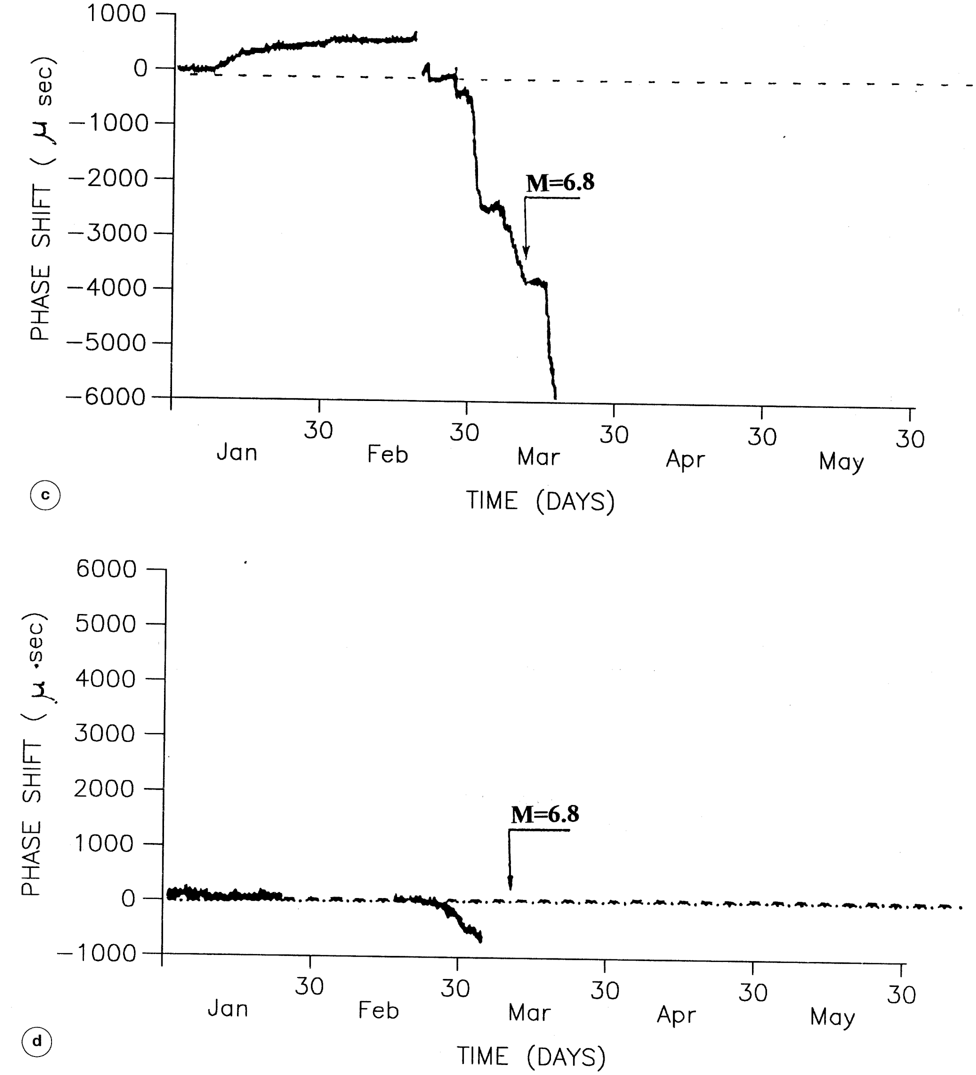

Fig. 2c,d. The effect of prolonged loss of phase cycles along the VLF radio wave routes controlled by the NSSP during the Erzincan earthquake (March 13, 1992, Turkey, $M_S = 6.8$) preparation and realisation. c) The radio wave route Aldra (Norway) - Yerevan; d) the radio wave route Tsushima Island (Japan) - Yerevan.

correspondingly, deteriorate their reception by the receiving Ч7-38 stations set either in a zone proximal to or immediately in the strong earthquake preparation zone.

It is interesting that the effect observed displays certain regularities. If attention is given to the character of the PCPL effect during the Erzincan (Turkey) earthquake preparation, it is clearly seen that along the Monrovia (Liberia) - Yerevan and Reunion Island (France) - Yerevan radio routes the above effect is characteristic for sharp $\Delta\varphi$ phase shift leaps towards its

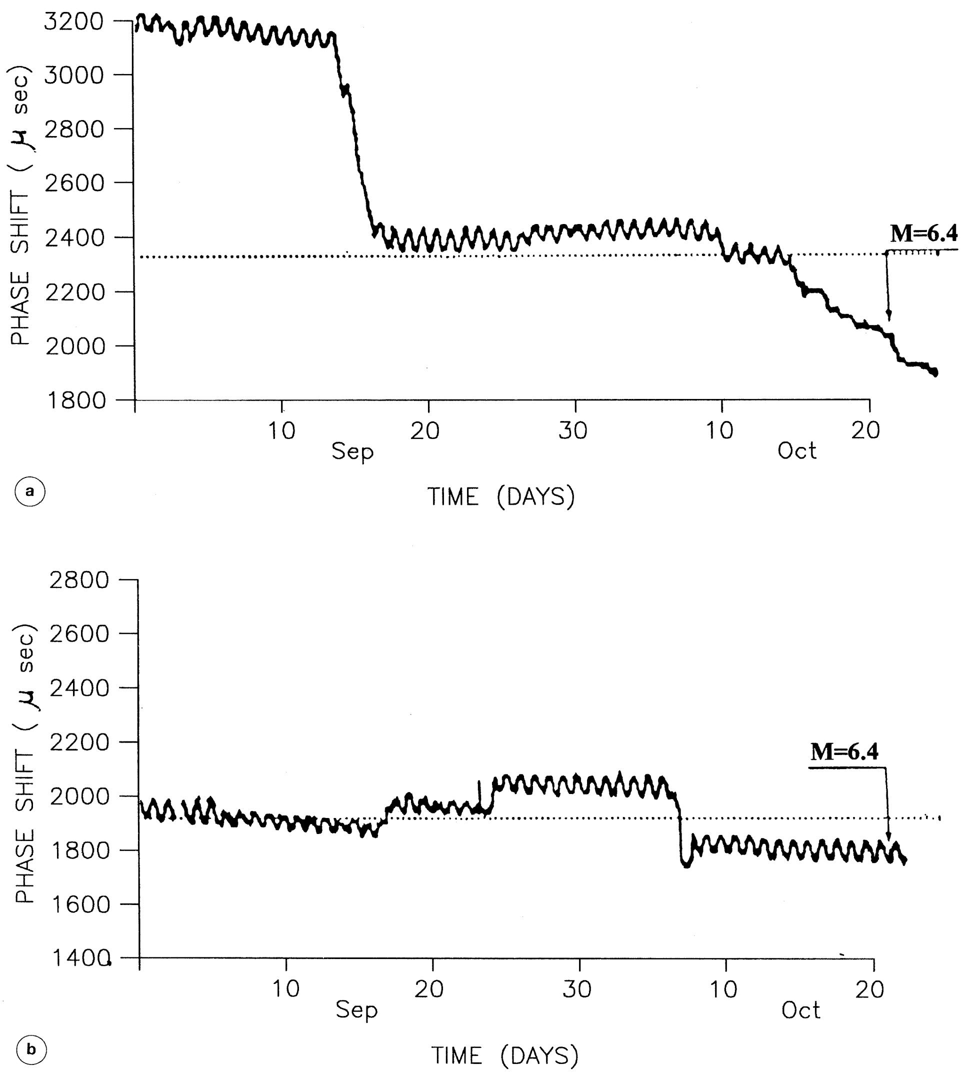

Fig. 3a,b. The effect of prolonged loss of phase cycles along the VLF radio wave routes controlled by the NSSP during the Barysakho earthquake (October 23, 1992, Georgia, $M_S = 6.4$) preparation and realisation. a) The radio wave route Monrovia (Liberia) - Yerevan; b) the radio wave route Reunion Island (France) - Yerevan.

positive sign build-up. Along the Aldra (Norway) - Yerevan and Tsushima Island (Japan) - Yerevan radio routes the PCPL effect is characterised by the same sharp $\Delta\varphi$ phase shift leaps directed, however, inversely, that is, towards the negative side.

Just the same PCPL effect is observed during the Barysakho (Georgia) earthquake preparation. However, the $\Delta\varphi$ phase shift leaps display the reverse pattern, that is, they are positive, along the Aldra (Norway) - Yerevan, Tsushima (Japan) - Yerevan routes and

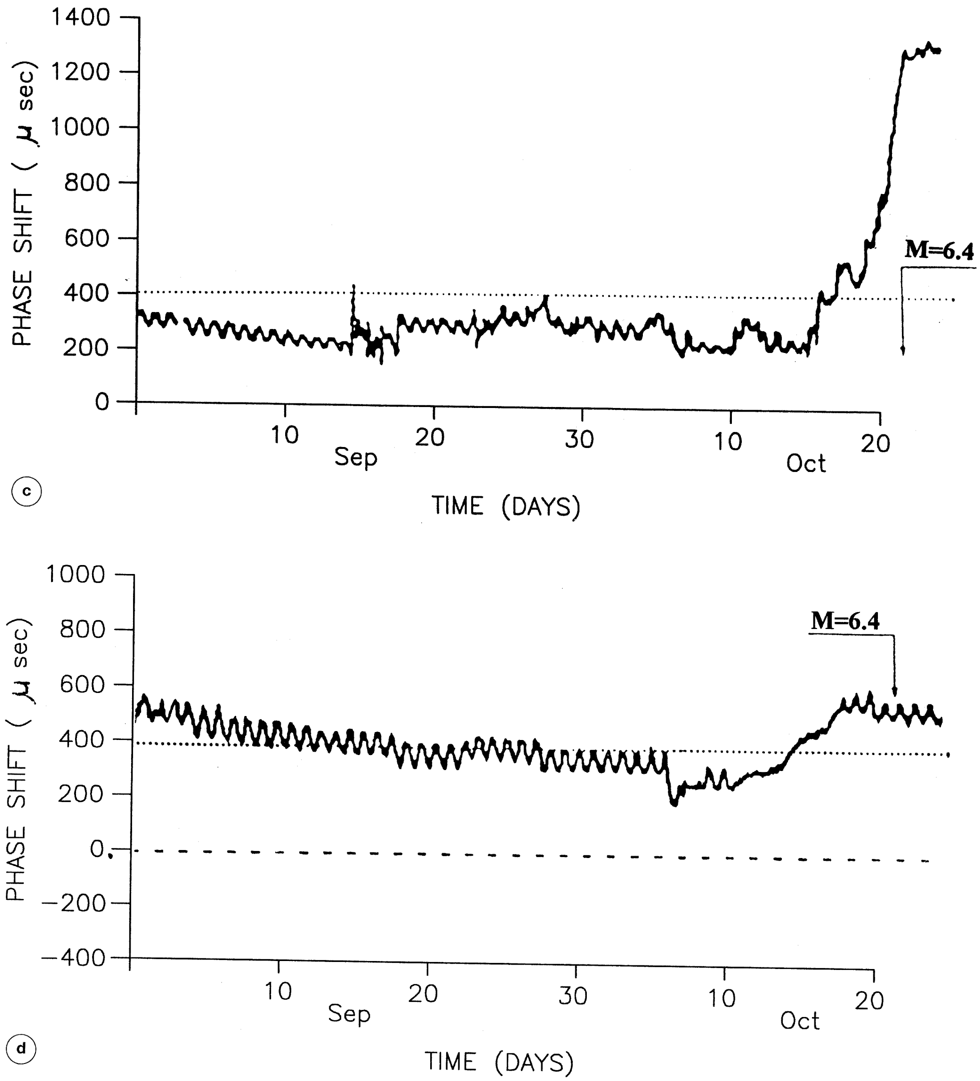

Fig. 3c,d. The effect of prolonged loss of phase cycles along the VLF radio wave routes controlled by the NSSP during the Barysakho earthquake (October 23, 1992, Georgia, $M_S = 6.4$) preparation and realisation. c) The radio wave route Aldra (Norway) - Yerevan; d) the radio wave route Tsushima Island (Japan) - Yerevan.

negative along the Monrovia (Liberia) - Yerevan and Reunion Island (France) - Yerevan routes.

Comparing these two PCPL effect patterns, it is apparent that the PCPL is positive at the pair of radio route receivers whose radio routes pass through the strong earthquake preparation zone. As regards the negative sign of the PCPL effect, this one is noted at the pair of receivers whose radio routes are oriented to the side opposing the earthquake preparation zone (figs. 1, 2a-d and 3a-d).

In addition to the PCPL effect observed only for the two cases described before, *i.e.* when the strong earthquake preparation zone was consistent with the area of antenna array, other ionosphere disturbances had been observed along the controlled radio routes during the preparation of remote earthquakes with regard to the earthquake receipt zone from 1991 till 1995.

As a rule, these were anomalies in the $\Delta\varphi$ daily variation night cycles, that had been noted by other researchers previously for different VLF radio wave radio routes crossing seismically active zones (Gufeld *et al.*, 1992). All observed types of those anomalies are presented in fig. 4.

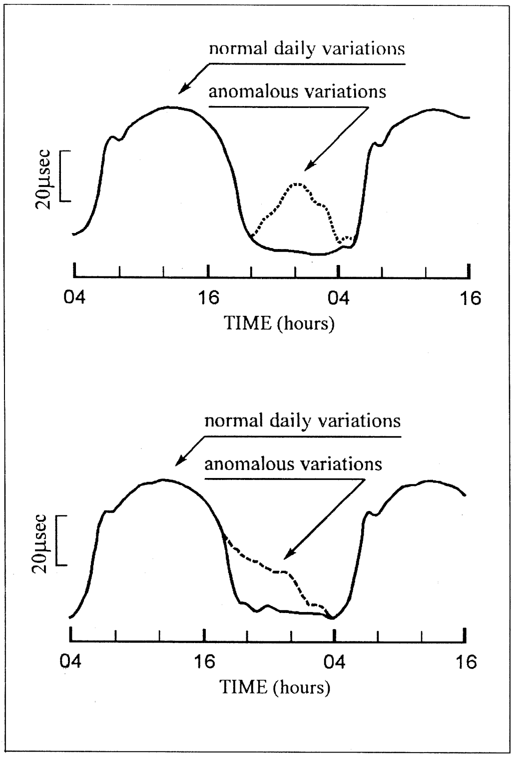

Fig. 4. The types of anomalies ($\Delta\varphi$ phase shifts) in the VLF radio wave propagation daily variations observed repeatedly for many days (3-30 days prior to the earthquakes of $M \geq 5.5$).

It should be noted that in all cases the $M \geq 5$ earthquakes took place only after the anomalies that repeatedly occurred during 4-15 days within 3-30 days prior to the seismic event displaying an amplitude up to 40-50% of daily $\Delta\varphi$ variations.

It should be particularly noted that single cases of strong anomalies not followed by $M \geq 5.5$ earthquakes as well as those when the $M \geq 5.5$ earthquake had not been preceded by anomalous ionosphere disturbances were observed along the controlled radio routes.

Assuming that anomalous values of $\Delta\varphi$ indicated in figs. 2a-d, 3a-d and 4 are of seismogenic nature since they preceded the $M \geq 5.5$ earthquake with epicentre located not further than three Frenel zones from the radio route for the 70-90% of cases (depending on the radio route), the aforementioned variations from the general rule can find their explanation. The cases of strong seismic event absence after the strong ionosphere disturbances may be associated with creep movements, while the case when the $M \geq 5.5$ seismic event is not preceded by abnormal disturbances may be determined by the properties of the medium in the earthquake preparation zone.

To conclude, fig. 5 shows daily $\Delta\varphi$ variations lasted for many days along the Aldra (Norway) - Yerevan route for which no seismic event with $M \geq 5.5$ was recorded in 1994. A total absence of any $\Delta\varphi$ anomalies of the PCPL type (figs. 2a-d and 3a-d) or like those indicated in fig. 4, given the absence of seismic events, attests the probable seismogenic nature of ionosphere disturbances noted during strong seismic event preparation.

The long-standing (1991-1995) parameter observations of the VLF radio wave propagation on the radio routes crossing the seismic zones carried out by the NSSP indicate that for 70-90% of situations (depending on the radio route) the disturbance of VLF wave propagation precedes a $M \geq 5.5$ seismic event which indicates the ionosphere violation coinciding in time with the period of strong earthquake preparation.

The new data obtained as a whole correspond to and supplement the observations made previously on the state of the ionosphere

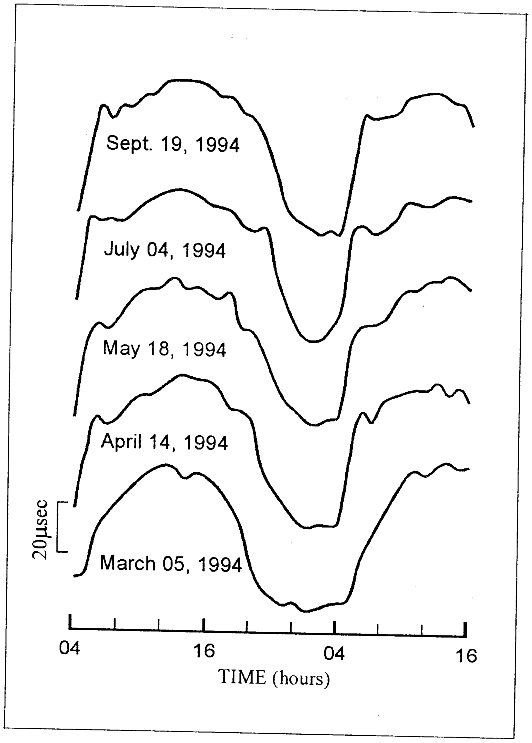

Fig. 5. Normal daily variations ($\Delta\varphi$ phase shifts) in the VLF radio wave propagation along the Aldra (Norway) - Yerevan radio route for which no $M \geq 5.5$ earthquakes were observed during 1994.

above the seismogenic zones living through strong earthquake preparation periods.

The seismogenic character of ionosphere disturbances during strong earthquake preparation could be proved finally only after complete theoretical substantiation of the observed phenomenon is given and new confirming experimental data provided not only by the VLF radio wave method but by other more direct methods of observation of ionosphere condition.

3. Ionosphere excitation possibility: the theoretical substantiation

In the geologic medium one or several groups of identically oriented ZSCs are formed first. Further, the zone of identically oriented ZSCs grows gradually with the increase in deforming elastic strain field force. By the time of rock rupture, during the strong earthquake preparation, the area of identically oriented ZSCs ranges up to its maximum size.

From the standpoint of physics, the explanation is that under the action of increasing elastic strains in the strong earthquake preparation zone an energy-active formation (body) consisting of uniformly oriented ZSCs comes into being. The size of this formation keeps growing continuously up to the rock rupture time, *i.e.* up to an earthquake.

As the dimensions of the uniformly oriented ZSC area enlarge, the values of its electric characteristics – inductance (L) and capacity (C) – build up, too. The former emerges from the comparison of the two known expressions for magnetic field energy:

$$W_{\mathrm{mag}} = LI^2/2 \tag{3.1}$$

where I is the current strength,

$$W_{\mathrm{mag}} = (\mu H^2/8\pi) \cdot V \tag{3.2}$$

where μ is the magnetic permeability of the medium, H is the magnetic field intensity, V is the volume of the uniformly oriented ZSC area.

Secondly, from the comparison of the two accepted expressions for electric field energy:

$$W_{\mathrm{el}} = CU^2/2 \tag{3.3}$$

where U is the tension value,

$$W_{\mathrm{el}} = (\varepsilon E^2/8\pi) \cdot V \tag{3.4}$$

where ε is the medium dielectric permeability, E is the electric field intensity.

The rise in the values of L and C electric characteristics' attendant with the increase in uniformly oriented ZSC area dimensions causes decay of natural frequencies associated to this area (f_0) since

$$f_0 = 1/(2\pi \sqrt{LC}, \tag{3.5}$$

and the corresponding increase in the radiation wave (λ_0).

An accurate quantitative calculation of λ_0 is generally an independent and complicated task, since L and C as well as R (the resistance) are the magnitudes arranged in space and dependent on the frequency. Nevertheless, simple estimations can be made to calculate λ_0 if the L-C circuit is likened to a certain resonator. In such case the λ_0 value is estimated by a simple $\lambda_0 \cong 2l$ relationship, where l corresponds to the linear dimension of the uniformly oriented ZSC area. Taking it into consideration that a strong earthquake of $M = 7.0$ is matched on average with a 35 km long rock rupture, a conclusion can be drawn that the linear dimension of a uniformly oriented ZSC area should fall on average within the limits of $l \cong 35$ km.

Here, the radiation wavelength in the area of uniformly oriented ZSCs is $\lambda_0 \cong 70$ km.

In this way a low frequency radiator that emits electromagnetic radiation most effectively propagating in the atmosphere is formed under the action of elastic strains due to the effect of uniformly oriented ZSCs during strong earthquake preparation in a seismically active zone.

The efficiency of very low frequency wave propagation ($\lambda_0 \cong 70$ km) with a quasi-square wave-front in the atmosphere is determined by the maximum quality of Earth-ionosphere spherical resonator and weak influence of such factors as diffraction and dissipation over the atmospheric inhomogeneities.

Reasoning from the above, setting a task on the character of very long electromagnetic wave propagation from the seismogenic source in the atmosphere is apparently required.

The equation describing propagation of electromagnetic waves for the quasi-static case and for the case of wave front perpendicular to the Earth surface is as follows (Levich, 1969):

$$\frac{d^2E(z)}{dz^2} = i\frac{4\pi\mu\,\sigma(z)\,\omega}{c^2}E(z), \qquad (3.6)$$

where:

E is the electric field intensity;

$\mu \cong 1$ is the magnetic permeability of the atmosphere;

$\sigma(z) = \sigma_0 \exp(z/h)$ is the atmosphere conductivity in the direction perpendicular to the Earth surface (z);

$\omega = 2\mu f_0$ is the field angular frequency;

c is the light speed;

h is the scope of atmosphere electric conductivity inhomogeneity.

The general solution of eq. (3.6) given the exponential law of $\sigma(z)$ changes with height (Barsukov, 1991) is as follows (Kamke, 1965):

$$E(z) = C_1 J_0\left((1+i)\frac{2h}{\delta}e^{z/2h}\right) + C_2 Y_0\left((1+i)\frac{2h}{\delta}e^{z/2h}\right) \qquad (3.7)$$

where $\delta = c/\sqrt{2\pi\mu\sigma\omega}$, $J_0(z)$ and $Y_0(z)$ – are Bessel's functions of zero order, first and second kind correspondingly, $C_{1,2}$ – are constant coefficients, defined by boundary conditions (one of them is $E(z) \to 0$, given $z \to \infty$).

Far from the Earth surface the arguments of Bessel's function are much greater than 1, so it can be easily supposed that asymptotic expression could be implemented

$$J_0(z) \cong \sqrt{\frac{2}{\pi z}}\cos\left(z - \frac{\pi}{4}\right),$$

$$Y_0(z) \cong \sqrt{\frac{2}{\pi z}}\sin\left(z - \frac{\pi}{4}\right). \qquad (3.8)$$

After substituting the value of argument z from (3.8), $E(z)$ takes a form:

$$E(z) \cong a_1 e^{-z/4h}\cos\left[(1+i)\frac{2h}{\delta}e^{z/2h}\right] + a_2 e^{-z/4h}\sin\left[(1+i)\frac{2h}{\delta}e^{z/2h}\right] \qquad (3.9)$$

where a_1 and a_2 are new constants.

Defining sin and cos, calculating the electric field modules square (intensity) we obtain that an exponential term $e^{-z/2h}$ is multiplied by the sum of two terms. One of them oscillates according to the $\sin\left(\frac{2h}{\delta}e^{z/2h}\right)$ and $\cos\left(\frac{2h}{\delta}e^{z/2h}\right)$

law, while the second grows rapidly obeying the $\mathrm{ch}\left(\frac{2h}{\delta}e^{z/2h}\right)$ and $\mathrm{sh}\left(\frac{2h}{\delta}e^{z/2h}\right)$ law.

As far as the second term grows faster than $e^{-z/2h}$ it has no physical meaning. What this means is that the coefficient preceding the second term shall be equal to 0. If this is the case

$$|E(z)|^2 \cong Ae^{-z/2h}\cos^2\left(\varphi+\frac{2h}{\delta}e^{z/2h}\right) \quad (3.10)$$

where A and φ are constants.

Expression (3.10) indicates that on average the electric field attenuates according to the exponential law.

More interesting, however, is in our opinion the result that the field value $E(z)$ due to $\cos^2\left(\varphi+\frac{2h}{\delta}e^{z/2h}\right)$ term rapidly oscillates as z height increases.

Therefore expression (3.10) proves that low frequency electric field $E(z)$ radiated by the seismogenic nature source (the area of uniformly oriented ZSCs) experiences strong oscillations in higher atmosphere layers during earthquake preparation.

Taking into account that in high atmospheric layers, at the level of a highly conductive ionosphere, the electric field intensity constitutes rather small values, it is not difficult to suppose that strong (3.10) oscillations of low frequency electromagnetic wave reaching the ionosphere, from the seismogenic source, may cause significant ionosphere disturbances.

Thus, the experimentally obtained data concerning the disturbed propagation of VLF radio wave in seismically active zones during the preparation of strong earthquakes have a satisfactory theoretical substantiation.

The disturbances in propagation of VLF radio waves may have a seismogenic nature. This is a result of ionosphere disturbances over a seismic event preparation zone. These ionosphere disturbances are influenced by strong oscillating low-frequency electromagnetic waves coming from singly orientated ZSC in seismogenic zone.

4. Effect of ZSC mutual polarisation in seismically active zone. Theoretical concepts

When considering the deformation process of geological medium at molecular level, *i.e.* at the ZSC level, it is necessary to mention that in the locally high concentration ZSC with power-active points (Balassanian, 1994), an effect of ZSC mutual overlapping may be expected. Under the influence of increasing elastic strains, the ZSC mutual overlapping results in the effect of ZSC mutual polarisation, and, correspondingly, the non-linear increase in electric field strain in the ZSC high concentration level zone.

If the field intensity in a medium volume unit involving n quantity of ZSC is noted by E, then (Balassanian, 1992-1994)

$$E = E_0 + E_{\mathrm{INP}}, \quad (4.1)$$

where E_0 is the intensity of homogeneous medium field; E_{INP} is the field intensity of naturally induced ZSC polarisation under the action of increasing elastic strains

$$E_{\mathrm{INP}} = -4\pi\overline{P}_{\mathrm{INP}}, \quad (4.2)$$

$\overline{P} = P_{\mathrm{INP}}/3$ is the mean dipole moment of medium volume unit

$$P_{\mathrm{INP}} = N\mu E_0, \quad (4.3)$$

N is the ZSC dipole elements number in the medium volume unit, μ is the sensitivity of each medium element with respect to the naturally induced polarisation process.

Substituting expression (4.2) into (4.1), allowing for $\overline{P} = P_{\mathrm{INP}}/3$ and substituting value E_0 (4.3) into (4.1) we have:

$$P_{\mathrm{INP}} = \left[\frac{N\mu}{1-(4\pi/3)N\mu}\right]\cdot E. \quad (4.4)$$

It follows from here that in accordance with (4.3) the sensitivity of the medium volume unit to the INP process is

$$M = N\mu \quad (4.5)$$

and can be expressed as

$$M \cong \frac{N\mu}{1-(4\pi/3)N\mu}. \tag{4.6}$$

If the concentration of dipole components (N) and, consequently, the ZSC concentration is small regardless of the seismic event preparation stage, then $(4\mu/3)N\mu \ll 1$ and this term can be discounted in the denominator of expression (4.4). In this case the medium is characterised by the linear relationship (4.3) between E and P_{INP} that is typical of E_{INP} weak quasi-linear field obeying Ohm's law. This field is spread over the whole seismically active zone at the early stage of seismic event preparation. The N concentration is initially high in the region of energy active point (which may be more than one). As the stress forces grow the N concentration in a volume unit increases up to the level when the term $(4\mu/3)N\mu \to 1$, while $M \to \infty$.

The latter implies polarisation catastrophe characterised by the disruption of E_{INP} and E linear relationship (expression (4.4)) and formation of a strong non-linear electric field subject to Poule's law.

According to Poule's law, a non-linear increase of electric field will continue till ZSC substance' break-down. It will simultaneously cause a strong non-linearity of the properties of the polarising medium (Conuell, 1970).

The first break-down of ZSC substance will create a strong displacement current of short duration j_{dis}

$$j_{\mathrm{dis}} = \frac{\partial P(t)}{\partial t}, \tag{4.7}$$

which is able to act like a trigger for propagation of a process of electrical break-down of ZSC substance along the whole zone that contains strongly polarised ZSC. As a result, in the local zone of ZSC high concentration discharge of accumulated electric energy and decay of the source of non-linear electromagnetic properties will occur.

The existence of local sources of non-linear electromagnetic properties in the seismic event preparation zone is verified experimentally in the NSSP of the Republic of Armenia.

For that purpose the INP method which was developed and successfully tested by Balassanian and Kobylsky was used (Balassanian 1990).

5. The new method of Irreversibility of Non-stationary Processes (INP) for revealing non-linear electromagnetic precursors of earthquakes

The INP (Irreversibility of Non-stationary Processes) method is designed to solve a broad scope of geophysical tasks, the object for investigation being non-linear elements of geologic medium which are formed by polarised ZSC.

The core of the method is that geologic medium non-linear element which is formed with polarised ZSC can be revealed by passing through it artificially excited unipolar stabilised pulses of current.

In case of the presence of a non-linear source in the observed domain, the form of the growth curve of non-stationary process excited in the medium (by current unipolar pulses) will differ from a form of a decay curve. In the non-linear medium a so-called private hysteresis loop of non-stationary process, also called the effect of non-stationary process (Balassanian, 1990) is observed.

Proceeding from the above, while exploring a medium in the zone of possible preparation of seismic event with the help of INP one can observe the process of forming and integration of non-linear electromagnetic sources, provided that they are really formed due to the effect of ZSC mutual polarisation in the seismic event preparation zone.

5.1. *The measurement procedure*

Measuring by the INP method involves periodical (according to the set protocol) sounding of the medium with rectangular 25 ms long pulses of electric current with relative pulse duration equal to 2. The sounding is achieved using the INP current generator: by means of contact (galvanic grounding-electrodes) and/or noncontact (inductive loop) procedures.

An electric potential difference (contact procedure) or an electromotive force (incontact procedure) induced in the medium by the sounding are measured by means of receiving electrodes (contact procedure) or a receiving loop (noncontact procedure), connected to the autonomous INP receiver.

The autonomous INP receiver implements a stroboscopic method of measuring input voltage amplitude increment ΔU at the fixed times t_i with respect to basic strobe pulse (t_i = 20 ms). The input ΔU_i voltage measurements are performed both during passing the current pulses and within the pause separating them.

As a result secondary electric or magnetic fields of non-stationary processes are studied.

In accordance with the INP method-based measurements the irreversibility parameters for the non-stationary processes as well as medium effective resistance, medium polarisability, dielectric loss tangent, rates of non-stationary process of making and droop, spontaneous polarisation potential difference and other electromagnetic parameters are estimated accurate to 5%.

The principal parameter of the INP that reflects the difference of shapes for non-stationary process of growth and decay curves for both electric and magnetic INP constituents is the equivalent of integral energy changes $E^{+(-)}$.

As the present work mentions only the INP observation results for the noncontact procedure, *i.e.* the changes of the INP magnetic component, for these measurements the $E^{+(-)}$ is estimated by the formula

$$E^{+(-)} = \frac{\sum\limits_{i=1}^{n-1} (dU_{t_i}^{m} - dU_{t_i}^{d}) \cdot dT_{i+1}}{\mu \cdot \mu_0 \, SI/2R}, \qquad (5.1)$$

where:

$dU_{t_i}^{m}$ is the voltage increment (in mV) measured under passing the current at the i time delay relative to the voltage in mV induced at the end of current pulse;

$dU_{t_i}^{d}$ is the voltage increment (in mV) measured after the current is cut off at the same i time delay relative to the voltage in mV induced at the end of the pause;

dT_{i+1} is the time interval separating $i+1$ and i time delays (s);

μ is the relative magnetic permeability for ordinary rocks ($\mu = 1$);

μ_0 is the permeability of vacuum ($\mu_0 = 4\pi\ 10^{-7}$ *H*/m);

S is the area of the receiving loop (m^2);

J is the amperage in the generator loop (mA);

R is the loop radius (m);

N is the number of delays in measurement time interval related to the pulse (pause) start.

The $E^{+(-)}$ reflects the difference of $dU_{t_i}^{m}$ curve shape from that of $dU_{t_i}^{d}$ curve. It can obtain both positive and negative values at the same observation point since positive (for E^+) and negative (for E^-) values of the magnitude $(dU_{t_i}^{m} - dU_{t_i}^{d})\, dT_{i+1}$ in the formula are summed up separately.

5.2. *Results of the observations*

The present work includes the INP method-based observation results for one of the NSSP observation sites («Jermouk» station) for the Tsovagiugh (M = 3.8) and Martouni (M = 5.0) earthquake preparation and realisation periods in the territory of Armenia (fig. 6).

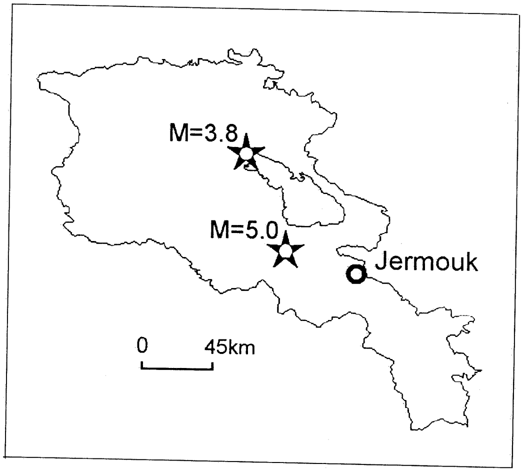

Fig. 6. Scheme of epicentres location of the Martouni (M = 5.0) and Tsovagiugh (M = 3.8) earthquakes in relation to the «Jermouk» observation station.

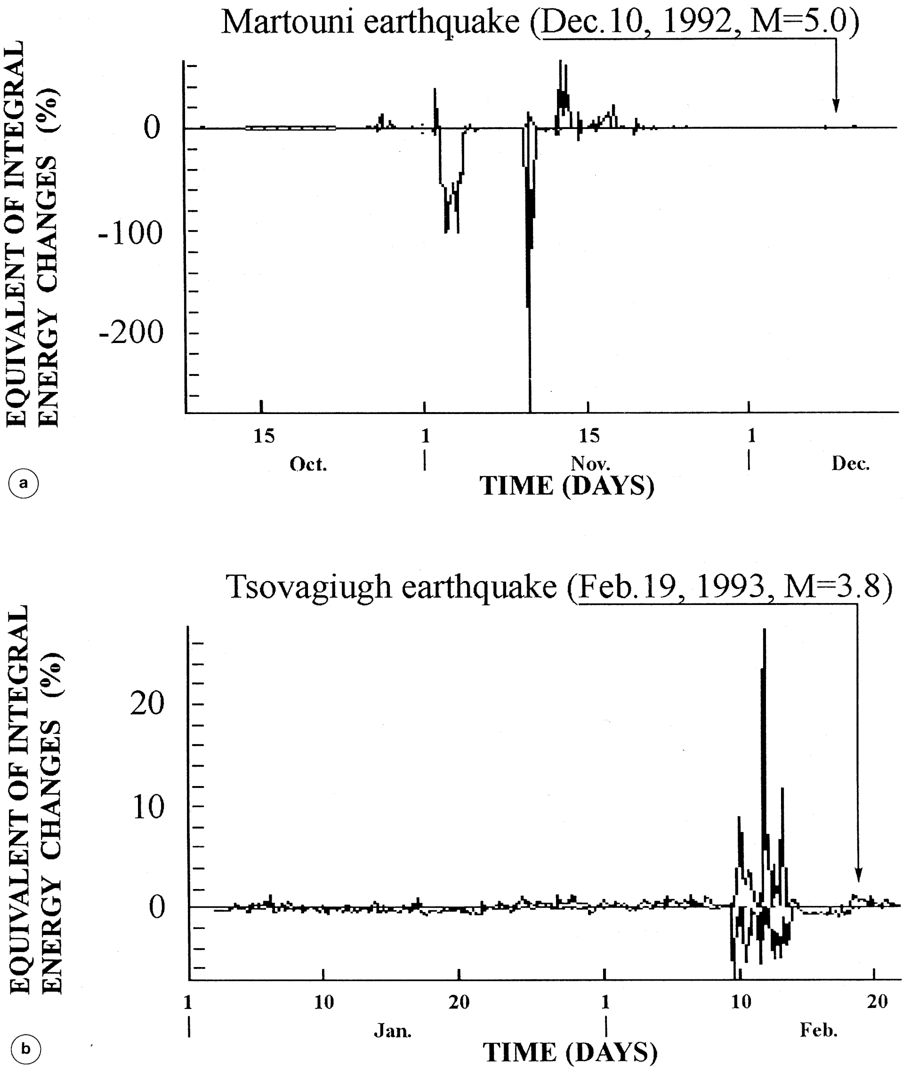

Fig. 7a,b. Anomalies of the parameter of the irreversibility of non-stationary processes ($E^{+(-)}$) at «Jermouk» station during the preparation of the Martouni (a) and Tsovagiugh (b) earthquakes.

From the data displayed in fig. 7a,b it is apparent that 10-40 days before those seismic events the «Jermouk» station observed intense parameter anomalies of the irreversibility of non-stationary processes ($E^{+(-)}$).

It is interesting that the Jermouk station had been performing measurements of soil gas Radon (*Rn*) (fig. 8a,b) and geomagnetic field variations (ΔT) (fig. 9a,b) at the same time.

As it is seen in figs. 8a,b and 9a,b the information on the preparation of Tsovagiugh and Martouni earthquakes based on Radon (*Rn*) and geomagnetic field (ΔT) variations is not

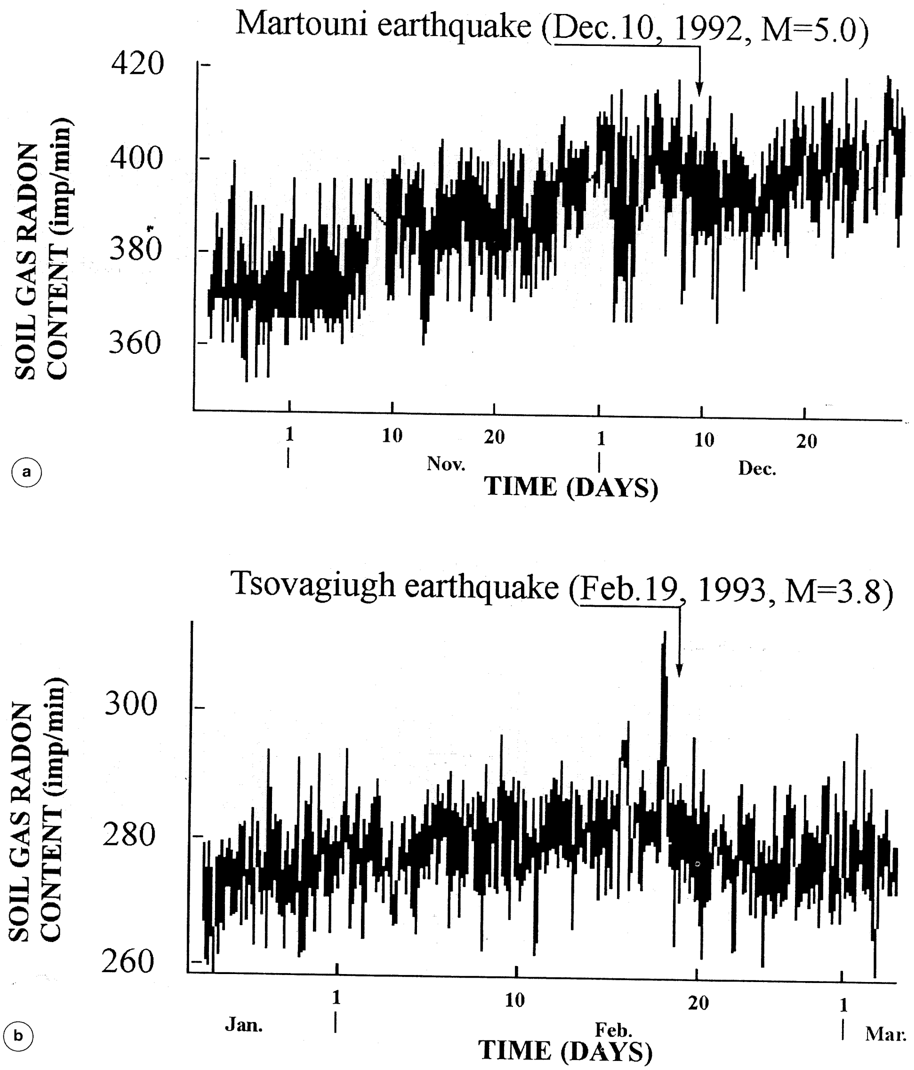

Fig. 8a,b. Soil gas Radon (*Rn*) variations at «Jermouk» station during the preparation of the Martouni (a) and Tsovagiugh (b) earthquakes.

comparable to the distinct INP parameter anomalies ($E^{+(-)}$).

Proceeding from the above, the INP method may appear more sensitive with respect to the deformation of geologic medium in the earthquake preparation zone than the traditional geophysical and geochemical methods.

The way of revealing strong earthquake precursors at the level of SCZ deformation in a geologic medium under the action of increasing elastic strain forces in the earthquake preparation zone seems to be promising.

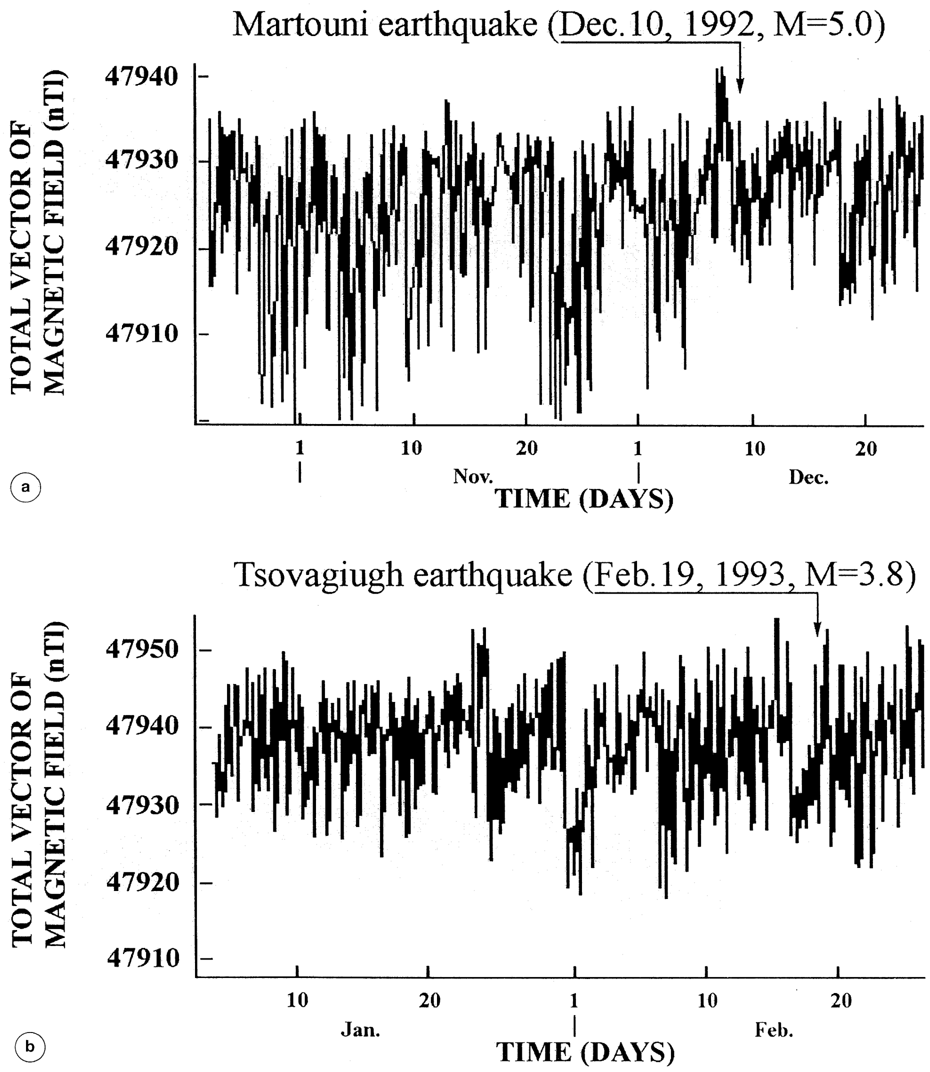

Fig. 9a,b. Variations of total strain vector of the geomagnetic field (ΔT) at «Jermouk» station during the preparation of the Martouni (a) and Tsovagiugh (b) earthquakes.

6. Conclusions

1) The long-standing (1991-1995) parameter observations of the VLF radio wave propagation on the radio routes crossing the seismic zones carried out by the NSSP indicate that for 70-90% of situations (depending on the radio route) the disturbance of VLF wave propagation precedes a $M \geq 5.5$ seismic event that indicates the ionosphere violation coinciding in time with the period of strong earthquake preparation. The new data obtained as a whole correspond to and supplement the observations made previously on the state of the ionosphere

above the seismogenic zones living through strong earthquake preparation periods.

2) The experimentally obtained data concerning the disturbed propagation of VLF radio waves in seismically active zones during the preparation of strong earthquakes have a satisfactory theoretical substantiation. The disturbances in propagation of VLF radio waves may have a seismogenic nature. This is a result of ionosphere disturbances over a seismic event preparation zone. These ionosphere disturbances are influenced by strong oscillating low-frequency electromagnetic waves coming from singly orientated SCZ in a seismogenic zone.

3) The geological medium deformation process in the strong seismic event preparation zone is accompanied by ZSC mutual overlapping in local zones of ZSC high concentration. ZSC mutual overlapping under the action of increasing elastic deformation forces leads to the effect of ZSC mutual overlapping and, correspondingly, to the formation of local sources of non-linear electromagnetic properties in the ZSC high concentration zone.

4) Formation of local sources of non-linear electromagnetic properties during the period of seismic event preparation is shown experimentally by the INP method. The INP method may appear more sensitive with respect to the deformation of geologic medium in earthquake preparation zone than the traditional geophysical and geochemical methods. The way of revealing strong earthquake precursors at the level of SCZ deformation in a geologic medium under the action of increasing elastic strains in the earthquake preparation zone seems to be promising.

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