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Chapter 12

Intelligent Seismic-Acoustic System for Identifying the Area of the Focus of an Expected Earthquake

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Additional information is available at the end of the chapter

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Abstract

Over the last few years, the following theoretical and practical research, technologies and algorithms have been developed allowing one to determine characteristics of noise contained in noisy seismic-acoustic signals. These characteristics (noise variance, cross-correlation function between the useful signal and the noise, relay estimations, etc.) are used to indicate the start of anomalous seismic processes (ASPs) as the earthquake preparation process. Using these characteristics, technologies for determining informative attributes of identification of the latent period of origin of ASPs have been developed. Based on those technologies, stations for robust noise monitoring of ASPs have been created and are currently functioning in Azerbaijani. Noise monitoring of ASPs was conducted from 2010.07.01 to 2014.06.01 on nine such stations built at wells of varying depth. Based on the results of obtained experimental data, an intelligent system has been built. It allows identifying the location of the area of an earthquake 10–20 h in advance, using combinations of time of change in the estimate of correlation function $R_{X\varepsilon}(\mu)$ between useful signal $X(i\Delta\, t)$ and noise $\varepsilon(i\Delta t)$ of seismic-acoustic information received from different stations. In the long term, the system can be used by seismologists as a tool for determining the location of the area of an expected earthquake.

Keywords: seismic-acoustic signal, anomalous seismic process, informative attributes, earthquake focus, robust noise monitoring, intelligent system, correlation function

1. Introduction

Nature and origin of earthquakes are a subject of many research papers [1]. There is also a lot of material devoted to obtaining seismic information from the earth's deep layers [2, 3]. Seismic

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signals received during earthquakes are analysed by means of noise analysis [4–8], designing continuous monitoring system [9], earthquake damage assessment and damage minimization [10–12], wavelet transform and finite elements [13–15]. Earthquake prediction-related problems are treated as a primary trend of research [16–19]. Various means and tools have been and are being developed and commissioned [20–22], including earthquake early warning systems for general population, models and technologies for prompt response of rescue groups [23–27]. Despite all the efforts and achievements, we still fail to predict earthquakes early enough, the results of which can be catastrophic indeed.

The authors of references [9, 28, 29] suggest employing a seismic acoustic system to monitor earthquake origin. Such a system comprises nine stations performing robust noise monitoring of anomalous seismic processes (RNM ASP) as a single network. Experimenting on those stations carried out from July 2010 demonstrated that incipient ASPs lead to the appearance of a cross-correlation between noise and useful signal of seismic acoustic data.

Using the varying estimate of the cross-correlation function between useful signal and noise, each of the stations in the network separately is reliable enough to indicate the incipient ASP processes preceding earthquakes. Nevertheless, the accuracy of coordinates of a coming earthquake determined by means of those stations proves to be insufficient. However, it has been established by way of experiments that we can design an intelligent neural network system that would use these stations for locating the ASP area. The following is our thoughts on how to build the said system.

2. Problem statement

In the regions of high seismic activity, incipient ASPs usually cause an earthquake to occur after the normal seismic state period T_0, as period T_1 ends.

T_0 and T_1 have different duration, but to monitor the start of the ASP origin, we basically need a reliable indicator of the start of T_1, which is discussed in references [4, 9, 28].

In reference [9], the authors propose creating a technology and a system for registering the starting point of T_1. According to the experiments laid out in references [4, 9, 28], however, T_1 does not start only during ASP origin. Therefore, apart from registering the start of T_1, to monitor the start of incipient ASPs, we also need the changes in the estimate of the cross-correlation function $R_{X\varepsilon}(\mu)$ between the useful signal $X(i\Delta t)$and the noise $\varepsilon(i\Delta t)$ to be indicated.

In the following paragraphs, we will use the estimate $R_{X\varepsilon}(\mu)$ of the seismic-acoustic signal $g(i\Delta t)$ as an informative attribute to indicate the beginning of the ASP origin. To do that, we must calculate $R_{X\varepsilon}(\mu)$ while monitoring.

Further on, practical use of the RNM ASP network also requires a technology for finding the location of the earthquake zone. To this end, we must first review the known methods designed

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to calculate the focus of an earthquake [30, 31] based on seismic data acquired by means of regular above-ground stations.

In that case, we find the focus of an earthquake from the difference between the amounts of time it takes *P* and *S* waves to reach each of the above-ground stations. The velocity of *P* wave propagation is higher than that of *S* wave propagation. The velocity of *P* wave in a homogeneous isotropic medium is

$$v_P = \sqrt{\frac{k + \frac{4}{3}\mu}{\rho}}, \tag{1}$$

where k is the volume factor, μ is the shear modulus and ρ is the density of the medium that waves penetrate.

The velocity of *S* wave propagation is

$$v_S = \sqrt{\frac{\mu}{\rho}}, \tag{2}$$

where μ is the shear modulus and ρ is the density of the material penetrated by the waves.

The distance from a regular above-ground seismic station to the focus is determined by multiplying the time difference by the difference in velocity:

$$S = \Delta T(v_p - v_s). \tag{3}$$

After the distance between the epicentre and the different seismic stations has been determined, the coordinates of the focus are found geometrically. Unfortunately, in all known cases, the coordinates of epicentres and hypocentres in seismic monitoring systems are determined after actual earthquakes.

Our experimental research showed that, for many reasons, it is practically impossible to use the obtained results to calculate the coordinates of the ASP areas on RNM ASP stations by means of the said technology.

Therefore, the present paper poses the problem of developing an intelligent neural network system for monitoring the ASP origin, identifying the location of the area and determining the approximate magnitude of an anticipated earthquake.

3. Determining the informative attributes of the hidden period of ASP origin

As ASP emerges at the start of T_1, the first estimates to change are those of cross-correlation function $R_{X\varepsilon}(\mu = 0)$ between useful signal $X(i\Delta t)$ and noise $\varepsilon(i\Delta t)$, variance D_ε of the noise and noise correlation $R_{X\varepsilon\varepsilon}(\mu = 0)$ [4, 9, 28]. This happens because noise$\varepsilon(i\Delta t)$ is formed due to the effects of the incipient ASP as period T_0 begins. Consequently, in T_1, a correlation emerges between useful signal $X(i\Delta t)$ and noise $\varepsilon(i\Delta t)$, causing an abrupt increase in the estimate $R_{X\varepsilon}(\mu)$. Therefore, we can consider $R_{X\varepsilon}(\mu)$ the main informative attribute and use it while monitoring the hidden period of ASP origin.

Starting from July 2010, we used traditional technologies as well as robust noise technologies on RNM ASP stations to detect the start of the hidden period of ASP origin. A sufficiently reliable registration of period T_1 by means of estimates obtained through traditional spectral and correlation technologies proved to be unattainable. The use of robust noise technology, however, caused an abrupt change in the estimate of the cross-correlation function $R_{X\varepsilon}(\mu)$ at the start of T_1. That was a crucial factor, adding to the validity of the monitoring. Considering that, we used $R_{X\varepsilon}(\mu)$ as an informative attribute in the monitoring of ASP origin, while creating the RNM ASP network.

The relay correlation function $R^*_{gg}(\mu = 0)$ between useful signal $X(i\Delta t)$ and noise $\varepsilon(i\Delta t)$ is

$$R^*_{X\varepsilon}(\mu = 0) \approx \frac{1}{N}\sum_{i=1}^{N}\left[\operatorname{sgn} g(i\Delta t)g(i\Delta t) - 2\operatorname{sgn} g(i\Delta t)g((i+1)\Delta t) + \operatorname{sgn} g(i\Delta t)g((i+2)\Delta t)\right]. \quad (4)$$

Knowing the estimates $R^*_{X\varepsilon}(\mu = 0), R^*_{gg}(\mu = 1), R_{gg}(\mu = 1)$ and considering the equality relationship between $R^*_{gg}(\mu = 1)$ and $R_{gg}(\mu = 1)$ and $R^*_{X\varepsilon}(\mu = 0)$ and $R_{X\varepsilon}(\mu = 0)$

$$\frac{R^*_{gg}(\mu = 1)}{R_{gg}(\mu = 1)} = \frac{R^*_{X\varepsilon}(\mu = 0)}{R_{X\varepsilon}(\mu = 0)}, \quad (5)$$

we can calculate $R_{X\varepsilon}(\mu = 0)$ from this formula:

$$R_{X\varepsilon}(\mu = 0) = \frac{R_{gg}(\mu = 1)R^*_{X\varepsilon}(\mu = 0)}{R^*_{gg}(\mu = 1)}. \quad (6)$$

We were able to conclude from our experiments that to achieve more trustworthy monitoring results, we should also use the estimates of noise correlation $R_{X\varepsilon\varepsilon}(\mu = 0)$ and noise variance D_ε as extra informative attributes. Those estimates are calculated from the following expressions [4, 9, 28]:

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$$R_{x\varepsilon\varepsilon}(\mu) = R_{x\varepsilon}(\mu) + D_\varepsilon = \frac{1}{N}\sum_{i=1}^{N}\left[g^2(i\Delta t) + g(i\Delta t)g((i+2)\Delta t) - 2g(i\Delta t)g((i+1)\Delta t)\right] \tag{7}$$

$$D_\varepsilon = R_{X\varepsilon\varepsilon}(\mu = 0) - R_{X\varepsilon}(\mu = 0). \tag{8}$$

As we can see, $R^*_{X\varepsilon}(\mu = 0)$, $R_{X\varepsilon}(\mu = 0)$, $R_{X\varepsilon\varepsilon}(\mu = 0)$ and D_ε are determinable from Eqs. (4), (6), (7) and (8). These estimates raise the validity of ASP monitoring to an adequate level.

4. Technology and systems for locating the ASP origin area

An earthquake takes place as soon as an ASP hits a critical point of development. Earthquake magnitude and the radius of its focus are contingent on the structure and nature of the strain-stress distribution in the rocks in a particular location. A jump-like rock deformation emits elastic waves. The amount of the deformed mass is a significant aspect that determines the intensity of the shock and the formation of noise $g(i\Delta t)$. Core bursts follow periods T_1 of earthquake preparation that can be as long as dozens of hours.

Analysing the seismic data from the acoustic sensors at suspended oil wells, we find that as ASPs start, seismic-acoustic noise travelling in the earth's deep layers anticipates the earthquake by dozens of hours [4, 9, 28]. Experiments show that RNM ASP stations can adequately monitor the beginning of T_1 by the above-described technology (**Figure 1**). Further on, we will consider working out an intelligent technology for locating the ASP area, using the data from the stations installed in nine seismically active regions of the Caspian Sea (**Figure 1**). The geographical coordinates and well depths of the stations are given in **Table 1**.

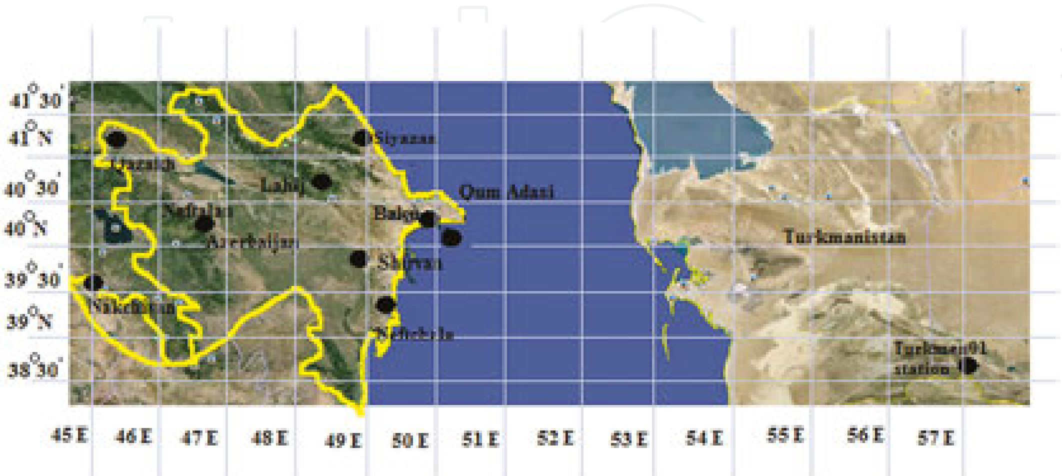

Figure 1. Map of the locations of RNM ASP stations in the seismically active region of the Caspian Sea.

No.	Station	Latitude	Longitude	Well depth	Start of operation
1	Qum Island	40.310425°	50.008392°	3500 m	July 2010
2	Siazan	41.046217°	49.172058°	3145 m	November 2011
3	Naftalan	40.609521°	46.791458°	4000 m	May 2012
4	Shirvan	39.933170°	48.920745°	4900 m	November 2011
5	Neftchala	39.358333°	49.246667°	1430 m	June 2012
6	Nakhchivan	39.718000°	44.876000°	1800 m	March 2013
7	Qazakh	41.311889°	45.108611°	200 m	August 2013
8	Turkmenistan	38.530089°	56.654472°	300 m	August 2013
9	Cybernetic	40.223252°	49.800833°	10 m	February 2014

Table 1. Geographical coordinates and well depths of RNM ASP stations.

According to the results of the experiments on the RNM ASP stations (**Figure 2**), the seismic noises caught by hydrophones from the earth's deep layers are immediate precursors of earthquakes.

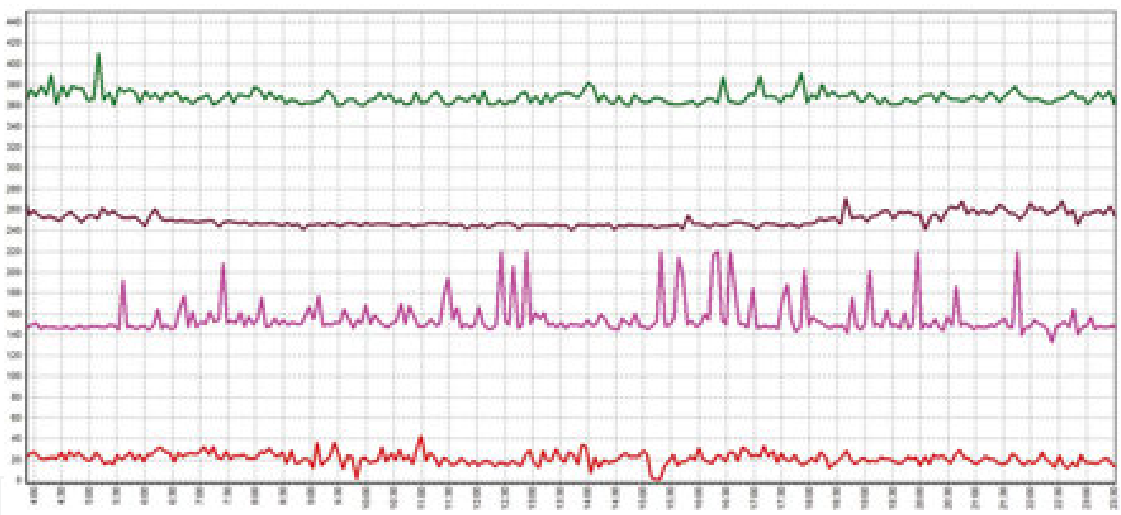

Figure 2. Siazan, Qum Island, Shirvan, Neftchala: 2013-03-26 Georgia-Russia.

Those noises were measured and analysed, and the relevant data was forwarded from the stations to the server of the monitoring centre (MC) on a high-speed radio channel via satellite. The received data can also be forwarded to other MCs in other countries of a particular region.

As seen from **Figure 1**, RNM ASP stations were put into operation one by one starting from July 2010: first at Qum Island, then in Shirvan, Siazan, Naftalan, Neftchala, Nakhchivan (on the borders with Turkey and Iran), Turkmen01 (in Turkmenistan), Qazakh (on the Georgian border) and Cybernetic (in Baku). The last three stand on 300-, 200- and 10-m deep water wells, respectively. Pipes in the wells naturally fill with water. Hydrophones were installed inside the pipes at 10–20 m from the water level. The built network of stations allowed us to conduct large-scale experiments that have demonstrated that the seismic-acoustic noises emerging during ASP origin spread within a 300–500 km radius many hours before the seismic waves can be detected by above-ground stations.

The operation of the network involves synchronous robust analysis of seismic-acoustic signals received from all stations. Values of noise parameters $R_{x\varepsilon}(\mu), R_{x\varepsilon\varepsilon}(\mu), D_{\varepsilon}$ are sent to the MC from the stations (**Figure 2**). By the changes in those estimates, the starting points T_{1i} and T_{1j} of ASP origin are indicated for the *i*th and *j*th stations, respectively.

We have established that each RNM ASP station separately can adequately indicate an incipient ASP, as well as that we can use the results obtained during the operation of the network as a basis to create an intelligent technology for locating the zone of an anticipated earthquake. For this purpose, the network first determines the combinations of indication moments T_{1i} and T_{1j}. Those combinations, together with the geographical coordinates of the stations are the source data used to locate the ASP origin area. For the results to be adequate and trustworthy, it is appropriate that, in addition to the combinations of indication moments, time differences $T_{1i} - T_{1j}$ should also be used for each chosen pair of stations. That is, the combination T_{1i}, T_{1j} alone is insufficient as source data; we also need to determine the difference in time of ASP indication between the stations $\Delta\tau_{ij} = \left(T_{1i} - T_{1j}\right)$.

It is not easy to accurately identify the start of the time of indication T_{1i} by means of the estimates of noise parameters. For this reason, our system duplicates the process of determining $\Delta\tau_{ij}$, when the time difference $\Delta\tau ij=(T_{1i}-T_{1j})$ is also determined, using the extreme value of cross-correlation function $R_{g_i g_j}(\mu_{max})$ between the signals $g_i(i\Delta t)$ and $g_j(i\Delta t)$ obtained from different combinations of stations. The following expressions are used for this purpose:

$$R_{g_i g_j}(\mu_{max}) = \frac{1}{N}\sum_{i=1}^{N} g_i(i\Delta t) g_j(i+\mu)\Delta t \tag{9}$$

$$R^*_{g_i g_j}(\mu_{max}) = \frac{1}{N}\sum_{i=1}^{N} g_i^2(i\Delta t) g_j^2(i+\mu)\Delta t \tag{10}$$

$$R^*_{g_i g_j}(\mu_{max}) = \frac{1}{N}\sum_{i=1}^{N} g_i\,(i\Delta t) g_j^2(i\Delta t) \tag{11}$$

Then the difference in the time of indication between different stations on the server of the monitoring centre is determined in the following order:

1. Finding the time of registration of the start of period T_{1i} of ASP origin by the first station Qum Island.

2. Finding the time of registration for each subsequent station (Shirvan, Siazan, Naftalan, etc.).

3. Finding the sets of estimates of cross-correlation functions $R_{g_v g_j}(i\Delta t)$, $R_{g_v g_j}(i\Delta t)$ by Eqs (9)–(11) and, choosing from the results the time shifts $\mu \cdot \Delta t$, at which the curve of the cross-correlation function has the peak value, i.e. the extreme value; using those time shifts to determine $\Delta\tau_{ij} = \left(T_{1i} - T_{1j}\right)$.

4. The found time differences $\Delta\tau_{1i} = \left(T_{1i} - T_{1j}\right)$ are used as source data to locate the ASP area.

We see that in our system (**Figure 2**), the values of the noise parameters $R_{X\varepsilon}(\mu)$, $R_{X\varepsilon\varepsilon}(\mu)$ and D_ε obtained by the RNM ASP stations are synchronously sent via satellite communication to the MC server. On the basis of the results, combinations of sequences of indication times T_{1i} T_{1j} and combinations of time differences $\Delta\tau_{ij}$ are formed and then used as source data in locating of the earthquake area.

Our long-term experiments on the stations were conducted from July 2010 to June 2014. They identified the following 13 seismically active zones in Azerbaijan and nearby regions within a 500–600 km radius around the network of the RNM ASP stations.

I. Turkmen coast of the Caspian Sea;

II. South of the Absheron peninsula (in the Caspian Sea);

III. North of the Absheron peninsula (in the Caspian Sea);

IV. Shirvan (region of Azerbaijan);

V. North-western regions of Azerbaijan;

VI. Southern regions of Azerbaijan;

VII. South of the Caucasus region of the Russian Federation;

VIII. North-eastern regions of Iran;

IX. North-western regions of Iran (near Tabriz);

X. Iranian-Iraqi-Turkish border;

XI. Northern regions of Iran;

XII. Eastern regions of Turkey;

XIII. Western regions of Georgia (Black Sea).

We have previously given some of the results obtained by means of the RNM ASP stations in those zones in [9].

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Those 13 zones have experienced many earthquakes with magnitude 3–4 in the last 1.5–2 years. Combinations of the sequence of the times of the ASP indication by Qum Island, Shirvan, Siazan, Neftchala, Naftalan and Nakhchivan stations for each of them practically overlapped. Analysing the records, we have concluded that each combination of the time of corresponds to one specific zone. After 2 years of working at the interpretation of the results of our experiments, we were able to accurately locate the zone of an expected earthquake instinctively, using those combinations. Realising that earthquake areas could be located with the help of expert systems (ESs), we established that it was possible to design an ES for seismologists to use a network of the RNM ASP stations as a toolkit in locating the area of anticipated earthquakes.

The foundation of the proposed experimental version of such an ES for locating the ASP area (ESILA) is the knowledge base (KB) consisting of sets W_1, W_2, W_3, ..., W_{13} of the locations of the respective areas. Elements of each set are built from the data in the charts containing the parameters of all earthquakes registered by the stations in the mentioned 13 areas from July 2010 up to this day. Elements of the base comprise the combination of the sequence of times T_{1i}, T_{1j} when ASP was registered, the combination of the differences in times of the indication $\Delta\tau_{ij}$, and the combination of the estimates of the cross-correlation function $R_{X\varepsilon}(\mu = 0)$. They also contain the value of magnitude M_i found during respective earthquakes by above-ground seismic stations, as well as earthquake date. If only one element is available, the KB has the following form:

$$
\begin{gathered}
W_1\left\{\begin{matrix} T_{11}^{1(1)} & T_{11}^{2(1)} & \dots & T_{11}^{6(1)} & M_1 \\ \Delta\tau_{11}^{1} & \Delta\tau_{21}^{1} & \dots & \Delta\tau_{61}^{1} & M_1 \\ R_{X\varepsilon}^{1(1)}(\mu=0) & R_{X\varepsilon}^{2(1)}(\mu=0) & \dots & R_{X\varepsilon}^{6(1)}(\mu=0) & M_1 \end{matrix}\right\} \\
W_2\left\{\begin{matrix} T_{11}^{1(2)} & T_{11}^{2(2)} & \dots & T_{11}^{6(2)} & M_2 \\ \Delta\tau_{11}^{2} & \Delta\tau_{21}^{2} & \dots & \Delta\tau_{61}^{2} & M_2 \\ R_{X\varepsilon}^{1(2)}(\mu=0) & R_{X\varepsilon}^{2(2)}(\mu=0) & \dots & R_{X\varepsilon}^{6(2)}(\mu=0) & M_2 \end{matrix}\right\} \\
\vdots \\
W_{13}\left\{\begin{matrix} T_{11}^{1(13)} & T_{11}^{2(13)} & \dots & T_{11}^{6(13)} & M_{13} \\ \Delta\tau_{11}^{13} & \Delta\tau_{21}^{13} & \dots & \Delta\tau_{61}^{13} & M_{13} \\ R_{X\varepsilon}^{1(13)}(\mu=0) & R_{X\varepsilon}^{2(13)}(\mu=0) & \dots & R_{X\varepsilon}^{6(13)}(\mu=0) & M_{13} \end{matrix}\right\}
\end{gathered}
\tag{12}
$$

Sets $W_1 - W_{13}$ of the experimental KB consist of dozens of elements and are updated with new ones during new earthquakes. After the monitoring and registration of the time of the start of a current ASP, the stations build current combinations of the sequence of the indication times

T_{1i}, T_{1j}, the combination of differences in the indication times $\Delta\tau_{ij}$, and the combination of estimates $R_{X\varepsilon}(\mu)$.

In January 2014, the experiments on locating the earthquake areas by means of ESILA started. The procedure is as follows. The monitoring results obtained by the RNM ASP network are used to form a current element, which is compared with those in the sets W_1, W_2, W_3, ..., W_{13} within the identification unit of the ES (IUES). Should there be any match, the zone of an earthquake is located based on the order number of the current element. The number of the zone is memorised in the ES decision-making unit (DMU) and the current element is saved in the set in the KB. In this manner, more and more elements are continuously saved into the KB while ESILA is functioning. The RNM ASP network and ESILA work as a unified system.

ESILA was tested during all subsequent earthquakes to confirm the adequacy and validity of the results it produces. It became obvious that it is really possible to practically use this experimental version to locate ASP zones. Therefore, the system can be useful for determining the areas of anticipated earthquake. With this in mind, the features of the DMU of ESILA were updated with the feature of compiling the following types of information and presenting it to seismologists:

1. Date of current ASP, the number of area of anticipated earthquake;
2. Current monitoring results from RNM ASP stations;
3. Assessed lead time at the start of ASP monitoring compared with the time of indication by above-ground stations;
4. Elements registered in the relevant set during the previous ASP in the assumed earthquake area (including dates);
5. The number of elements identical to the current ones;
6. Magnitudes of previous earthquakes;
7. Minimum magnitude of anticipated earthquake; and
8. If KB contains no elements identical at least to some elements in the sets W_1–W_{13}, DMU gives out the information that locating the earthquake area is impossible.

5. Technology for determining the approximate value of magnitude of an expected earthquake using a neural network

The analysis of the results of the experimental identification of the location of the ASP area has demonstrated that, with the current estimates $R_{X\varepsilon}(\mu)$, $R_{X\varepsilon\varepsilon}(\mu)$, D_ε and knowing the distance from the area to the RNM ASP stations, it is possible to determine the approximate value of the minimum magnitude of an expected earthquake using a neural network. Research shows that neural networks can be used for this purpose [32, 33]. It was found appropriate to use the

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information contained in the sets W_1–W_{13} to train neural networks. The block diagram of the neural network ($N3 = 1$) is functioning in the following way. The content of the corresponding elements of the sets $W_1, W_2, W_3, \ldots, W_{13}$ is transmitted to the outputs $X_1, X_2, \ldots, X_{N1}$ of the neuron, i.e. the combinations of times of the ASP indication T_{1ij}, differences of indication time $\Delta\tau_{ij}$ and the estimate $R_{X\varepsilon}(\mu = 0)$ are received at the inputs of the neuron one by one; the magnitude M_i of the earthquake registered by ground stations is established at the output of the neuron. The training is carried out successively from earthquake area I to earthquake area XIII. For instance, during the training of the neuron on area III, i.e. during the earthquake with the area in the Caspian Sea, the monitoring results obtained at the stations in Siazan, Qum Island, Neftchala and Turkmen01 (Turkmenistan) are successively transmitted from the KB to the inputs of the neuron. The value of the magnitude $M3$ is given to the output. During the training of the neuron to determine the magnitude in area XII, i.e. in East Turkey, then the monitoring data of Qazakh, Naftalan, Shirvan and Nakhchivan are sent to the input of the neuron and the magnitude $M12$ goes to the output. Thus, the parameters of the ASP previously registered by the RNM ASP stations are used for the neural network training. At the same time, the coordinates of the location of the earthquake areas are used in the DMU to determine the approximate distance S_I between the stations and the areas, which are also transmitted to the inputs of the neural network. Based on the source data written in the elements of the sets W_1–W_{13} and the distances S_1–S_9 from the ASP area to each station, the neural network learns to determine the approximate magnitude of an expected earthquake. Owing to this, after the training stage and in the process of the current monitoring of the ASP, when the current combinations of corresponding estimates are transmitted to the neuron outputs, the code of the corresponding magnitude M of the expected earthquake forms on the output y_3 [1]. The result is sent to the input of the DMU of ESILA.

During the operation of the neural network and the ES, every time the coordinates and approximate magnitude of every expected earthquake have been identified, the obtained results are compared with the coordinates and magnitude of actual earthquakes registered by ground seismic stations. The obtained difference is further used to correct the KB and in the training of the neural network. Therefore, the KB is improved in the course of time, with the training level of the neural network constantly improving. This results in increased reliability, authenticity and adequacy of identification of the location and magnitude of expected earthquakes.

Analysing the experience of the use of the ES in identifying the location of the area of the expected earthquake and of the neural network in determining its magnitude, we have established that to enhance the trustworthiness of the results we must increase the number of RNM ASP stations in the network. To this end, the Nakhchivan station near the border with Turkey and Iran and Turkmen01 station in Turkmenistan (**Figure 1**) were commissioned. In July 2013, the Qazakh station and Cybernetic station were built on the Georgian border (**Figure 1**) and at the Institute of Control Systems (Baku), respectively.

Experimental monitoring performed by the Cybernetic station installed in the basement of the Institute of Control Systems at a 10-m deep well gave the results that matched the readings of the Qum Island station standing at a 3500-m deep well.

6. Results of experiments on locating earthquake areas (January 2013–July 2014)

After the test operation of the system started in January 2013, certain identification errors were registered during weaker earthquakes. Errors in identification were also registered on two or three stations simultaneously due to a malfunction of the power lines, communication and hydrophone, controller and other units. No errors were detected for earthquakes with strength over five points, when the stations were operating normally.

Due to the length of the list of all identified locations of anticipated earthquakes for 2013–2014, we included in **Table 2** below only 10 locations for earthquakes with magnitude over five from the period from January 2013 to July 2014. **Figures 2–11** show the charts of ASPs that preceded those earthquakes. The first column of the table references data taken from the Euro-Mediterranean Seismological Centre (EMSC) website (http://www.emsc-csem.org/#2).

The time of the earthquakes in the table is in UTC, while the time in the charts is local (Baku time, UTC + 4).

Identified locations of anticipated earthquakes can be found in column 22. For authenticity, each row of the table is supported by a respective chart (**Figures 2–11**) drawn by the RNM ASP stations in the process of origin of a respective ASP.

Sign '*' implies that the response of a station to the incipient ASP of an anticipated earthquake was weak, sign '–' that the registered estimate of $R_{X\varepsilon}(\mu)$ is beneath the threshold value.

In Row 1 of **Table 2**, we see the results of the identification of location for the Georgian earthquake of 26 March 2013. **Figure 2**, in turn, shows that the earthquake start was registered at 04:15 by the Siazan station, at 04:30 by the Qum Island station, at 06:50 by the Shirvan station and at 08:30 by the Neftchala station. Naftalan station was not functioning at the time of that earthquake. Nevertheless, the system concluded that such manner of ASP registration corresponded to area VII. The ASP was registered 8–10 h before the earthquake occurred.

Row 2 contains the results of the identification of location for the Georgian earthquake of 28 May 2013. From the chart we can see that Siazan, Naftalan, Shirvan and Qum Island stations indicate the ASP origin over 20 h before the earthquake (even without the data from the malfunctioning Naftalan station). The northern (Siazan) and north-western (Qum Island) stations were the first to detect an anomaly. That being said, the RNM ASP stations indicated the start of ASPs in the following order: 07:30—Naftalan; 09:10—Siazan; 09:45—Shirvan; 11:40—Qum Island (**Figure 3**). The system located the zone of the earthquake by 18:00 (Baku time), i.e. 10–11 h before the above-ground stations.

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1	2	4	5	6	7	8	9	10	11	12
No.	Date, time, coordinates, magnitudes and depth of earthquake epicentre	$\Delta\tau_{12}$	$\Delta\tau_{13}$	$\Delta\tau_{14}$	$\Delta\tau_{15}$	$\Delta\tau_{16}$	$\Delta\tau_{17}$	$\Delta\tau_{18}$	$\Delta\tau_{19}$	$R_{X\varepsilon}$
1	2013-03-26, 23:35:25.0 UTC, 43.19 N; 41.67 E, mag 4.8, 10 km	35	−120	–	135	*	–	*	–	300
2	2013-05-28, 00:09:52.0 UTC, 43.22 N; 41.58 E, mag 5.2, 2 km	−115	−150	−250	–	*	–	*	–	150
3	2013-09-17, 04:09:13.0 UTC, 42.13 N; 45.80 E, mag 5.1, 2 km	–	−150	–	390	*	120	*	–	100
4	2013-11-24, 18:05:41.0 UTC, 34.06 N; 45.52 E, mag 5.6, 10 km	–	*	–	−10	−60	*	*	–	160
5	2014-01-10, 00:45:31.0 UTC, 41.86 N; 49.41 E, mag 4.8 80 km	–	20	–	110	*	–	−10	–	110
6	2014-01-14, 13:55:02.0 UTC, 40.33 N; 52.95 E, mag 5.2, 48 km	–	−45	*	−120	*	*	–	–	160
7	2014-01-28, 23:47:35.0 UTC, 32.45 N; 50.02 E, mag 4.9, 10 km	−135	–	–	100	−300	–	–	–	120
8	2014-02-10, 12:06:48.0 UTC, 40.23 N; 48.63 E, mag 5.4, 55 km	−300	–	–	–	45	75	–	–	75
9	2014-06-07, 06:05:32.4 UTC, 40.32 N; 51.58 E, mag 5.4, 44 km	145	20	–	−70	–	–	–	120	80
10	2014-06-29, 17:26:10.4 UTC, 41.62 N; 46.68 E, mag 5.1, 20 km	305	−85	–	–	–	315	*	–	100

13	14	15	16	17	18	19	20	21	22
No.	$R_{2X\varepsilon}$	$R_{3X\varepsilon}$	$R_{4X\varepsilon}$	$R_{5X\varepsilon}$	$R_{6X\varepsilon}$	$R_{7X\varepsilon}$	$R_{8X\varepsilon}$	$R_{9X\varepsilon}$	Number and location of the area of expected earthquake
1	50	100	–	140	–	–	–	–	Georgia (Sak'art'velo)
2	150	160	250	–	–	–	–	–	Georgia (Sak'art'velo)
3	–	40	–	80	–	80	–	–	Caucasus Region, Russia
4	–	–	–	150	250	–	–	–	Iran-Iraq Border
5	–	110	–	110	–	–	40	–	Caspian Sea, Offshore Azerbaijan
6	–	100	–	120	–	–	–	–	Turkmenistan
7	110	–	–	–	180	–	–	–	Western Iran
8	130	–	–	–	260	230	-	-	Azerbaijan
9	25	40	–	100	–	–	–	80	Offshore Turkmenistan
10	20	120	–	–	–	25	–	–	Azerbaijan

Table 2. Identified areas of expected earthquakes.

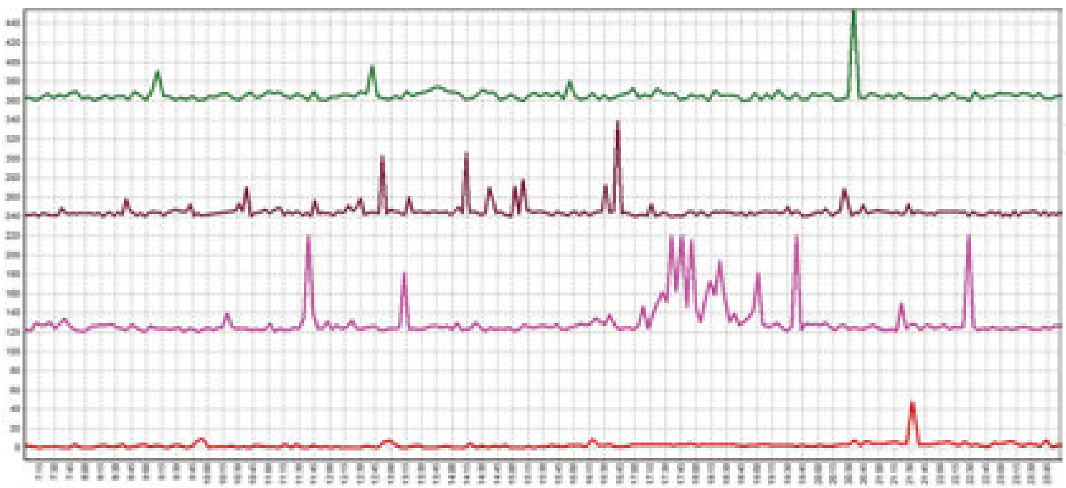

Figure 3. Siazan, Naftalan, Shirvan, Qum Island: 2013-05-27 Georgia (Sak'art'velo).

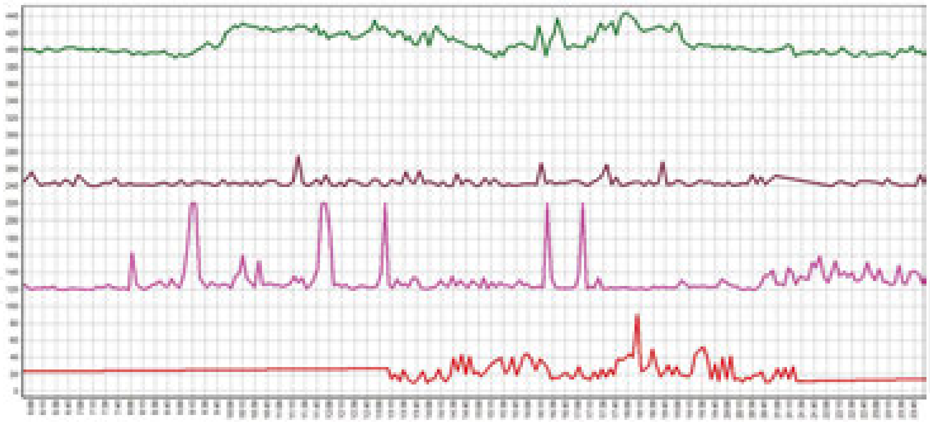

Figure 4. Qazakh, Siazan, Qum Island, Neftchala: 2013-09-16 Russia.

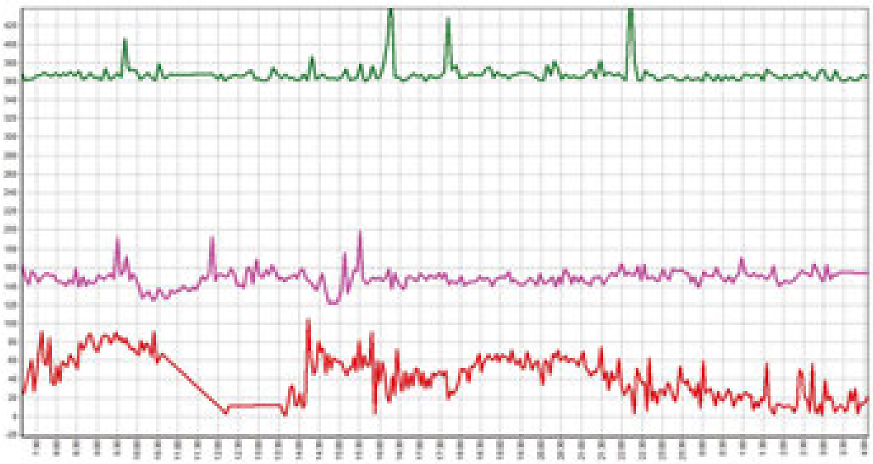

Figure 5. Qum Island, Neftchala, Nakhchivan: 2013-11-21 Iran-Iraq border.

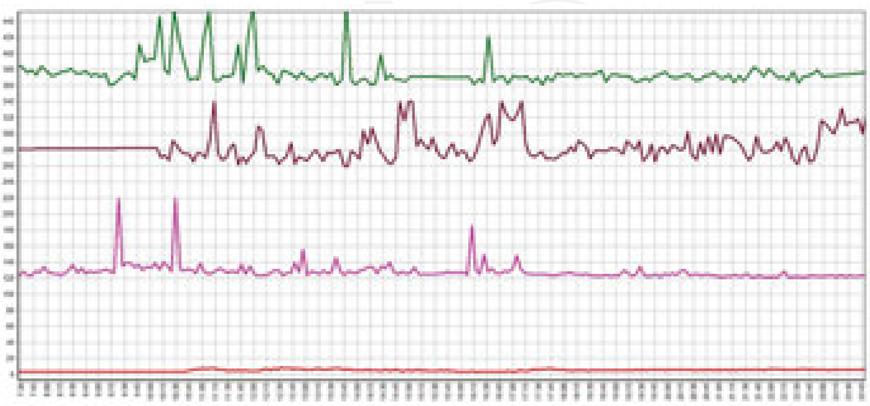

Figure 6. Siazan, Neftchala, Qum Island, Turkmen01: 2014-01-09 Caspian Sea, Offshore Azerbaijan.

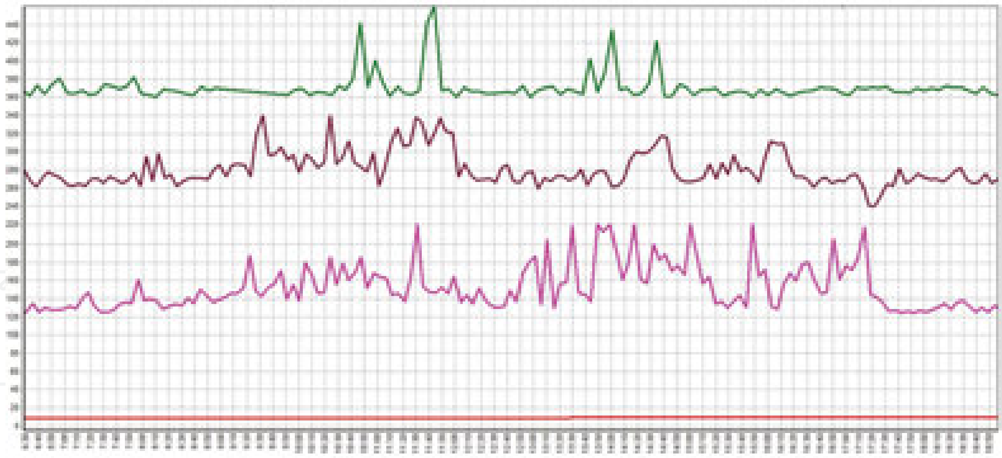

Figure 7. Siazan, Neftchala, Qum Island, Turkmen01: 2014-01-13 Turkmenistan.

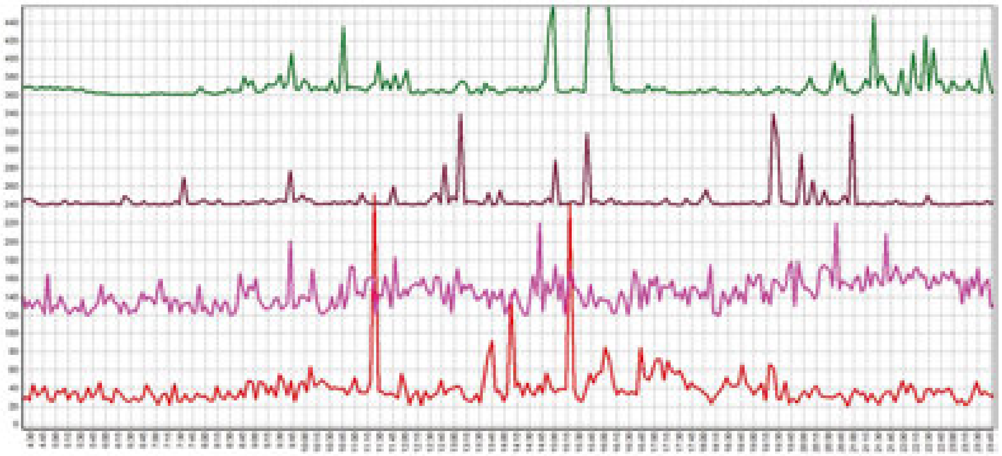

Figure 8. Qum Island, Shirvan, Nakhchivan, Neftchala: 2014-01-28 Western Iran.

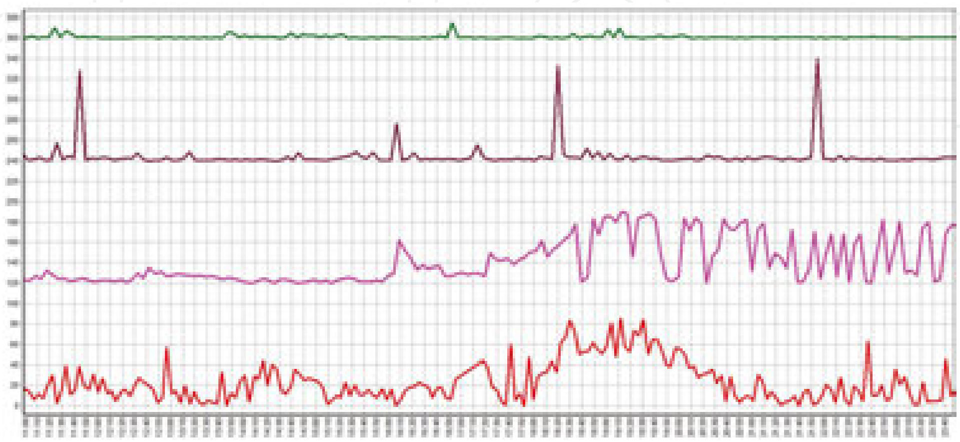

Figure 9. Qum Island, Shirvan, Qazakh, Nakhchivan: 2014-02-10 Azerbaijan.

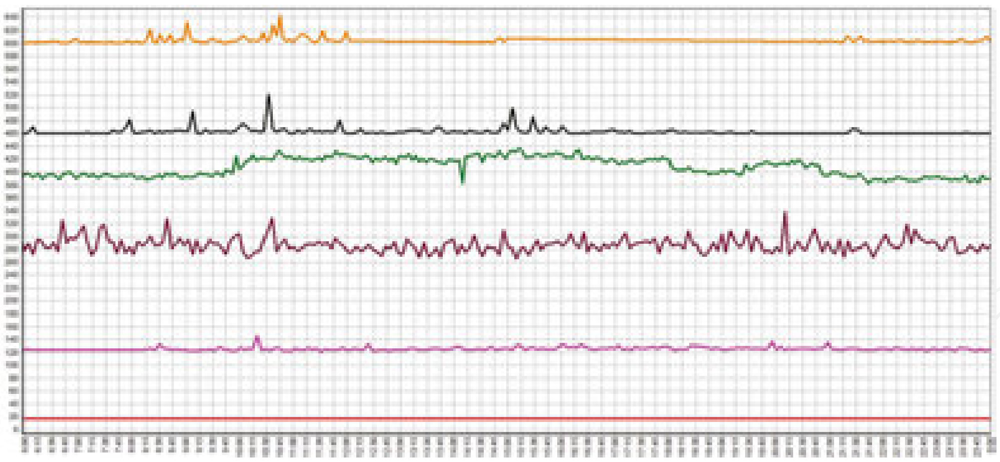

Figure 10. Siazan, Qum Island, Cybernetic, Neftchala, Shirvan, Turkmen01: 2014-06-06 Caspian Sea, Offshore Turkmenistan.

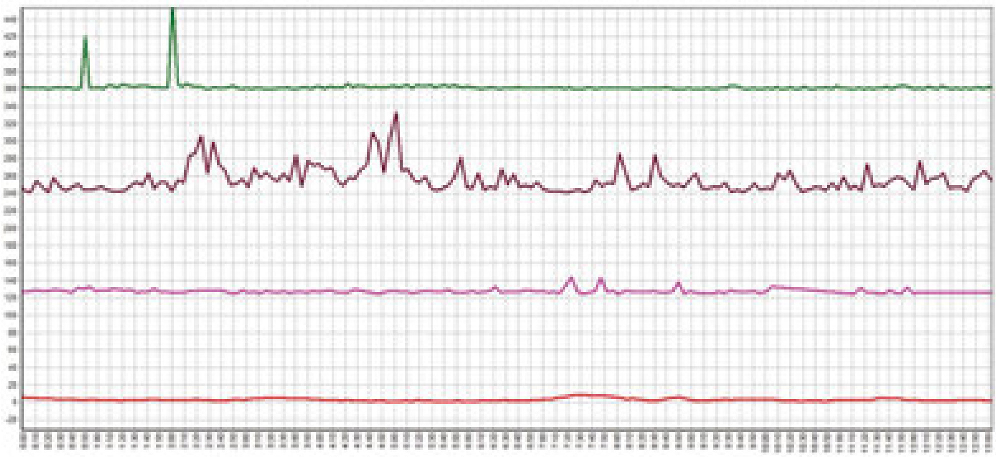

Figure 11. Siazan, Qum Island, Shirvan, Qazakh: 2014-06-29 Azerbaijan.

Row 3 presents us the results of the identification of location for the earthquake that took place on 16 September 2013 in the south of the Russian Federation.

From the charts of the third and fourth earthquakes (**Figure 4**), we can see that the ASP came from the south-east of the Caucasus and were recorded by the stations in the following order: Siazan—05:30, Qum Island—08:00, Qazakh—10:00, Neftchala—14:30. The system concluded that such a sequence corresponds to earthquake area VII, which is the north-east of Azerbaijan, where an earthquake did occur at 16:00/17:00 Baku time. The area was located at nearly 15 h before the actual earthquake.

Figure 5 shows that the system identified the coming earthquake area on the Iran-Iraq border from the combination of the times of ASP registration by the stations (Nakhchivan—08:00; Qum Island—09:00; Neftchala—08:50) 12 h before the earthquake.

Figure 6 relates to the earthquake that occurred at approximately 12:00 on 9 January 2014 in the Caspian Sea, Offshore Azerbaijan, and was registered 16 h before it occurred: by the Turkmen01 station at 09:15, by the Qum Island station at 09:25, by the Siazan station at 09:45, by the Neftchala stations at 11:15.

Row 6 of the table shows that the system identified the area of the expected earthquake in Turkmenistan. According to the chart in **Figure 7**, based on its sequence of registration by the stations (09:30 by Neftchala, 10:45 by Siazan, 11:30 by Qum Island), the system located the coming earthquake in Turkmenistan, i.e. in area I. The identification of the earthquake area took place over 24 h before the earthquake itself was registered.

Row 7 of the table contains the data related to the identification of location for the earthquake that occurred on 28 January 2014 in the western regions of Iran. According to **Figure 8**, based on the order, in which it was registered by the stations (Qum Island—09:45, Shirvan—07:30, Nakhchivan—04:50, and Neftchala—11:20), the system identified the location as area IX (Western Iran).

The data in Row 8 is related to the results of the identification of the area of the earthquake that occurred on 10 February 2014 in Azerbaijan. The curves of the chart (**Figure 9**) indicate that the sequence, in which the stations registered the ASP of that earthquake, was as follows: Qum Island—17:45, Shirvan—12:45, Qazakh—19:00 and Nakhchivan—18:30. Consequently, the system identified the area of the anticipated earthquake as area IV 19 h before the earthquake occurred.

Row 9 of **Table 2** contains the results of identification of the area for the earthquake that occurred on 7 June 2014 in Offshore Turkmenistan. The ASP of that earthquake was first registered by the Neftchala station at 06:45, then by the Qum Island station at 07:55, by the Siazan station at 08:15, by the Cybernetic station at 09:55, and finally by the Shirvan station at 10:20 (**Figure 10**).

The data in Row 10 is the results of the identification of the location of the anticipated earthquake that occurred on 29 June 2014 in Azerbaijan. **Figure 11** demonstrates that the order, in which an anomaly was registered by the stations, was as follows: Siazan—00:50, Qum Island—02:15, Shirvan—07:20, Qazakh—07:30. The system located the anticipated earthquake in area I (Azerbaijan).

7. Conclusions

1. The intelligent system based on the network of the RNM ASP stations and an ES combined with a neural network system can be used in locating the area of an anticipated earthquake. With the information on the direction and the number of the area of the anticipated earthquake, current combinations of the ASP, as well as the amount, list, date and magnitude of similar combinations registered in that area during previous earthquakes, a seismologist can assess the adequacy of the information on the location of the area of the anticipated earthquake. Having sufficient amount of time before the actual earth-

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quake, the seismologist can bring in other specialists to participate in the decision-making to exclude a chance of error.

2. The stations comprising the RNM ASP network in our system are installed on wells of varying depths. Therefore, they have different characteristics, which are not easy to account for while locating the area of an anticipating earthquake and finding its magnitude.

Besides, the deeper the well, the more expensive it is, which complicates the construction and maintenance of RNM ASP stations in the countries with no suspended oil wells available.

In view of the above, our recommendation for the future is to build a network of stations standing on 50–100 m deep water wells, in which hydrophones would be placed in the water column at a depth of 10–20 m. We have established experimentally that more trustworthy results would be obtained by a network consisting of a large number (more than 10–15) of stations installed on wells of equal depth and located at equal distance from one another. Expanding the RNM ASP network to the countries in several seismically active regions via satellite communication can, in the long term, give a significant improvement in the results of determining the coordinates of the location of an anticipated earthquake.

3. We have also established experimentally that the efficiency of ASP monitoring and identification of the location of the area of an anticipated earthquake is directly proportional to earthquake strength. With the earthquake intensity exceeding five points, the identification of the earthquake location almost always gives valid results. The value of the estimate of the cross-correlation function $R_{X\varepsilon}(\mu)$ between the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$ decreases as the distance from the earthquake area grows. The value of the estimate of noise variance D_{ε} increases with the distance from the area; the correlation $R_{X\varepsilon}(\mu)/R_{X\varepsilon\varepsilon}(\mu)$ decreases with distance and $D_{\varepsilon}/R_{X\varepsilon\varepsilon}$ increases. The speed, with which the seismic-acoustic noise spreads in different types of medium, e.g. water, sand or clay, substantially varies. The well depth and the radius of the ASP monitoring correlate.

4. According to the results of the experiments on the Qum Island station, the range of that station significantly exceeds that of the stations standing farther from the Caspian Sea. The Siazan and Neftchala stations are located near the Caspian Sea and also have a wider monitoring range compared with other stations. Practically all seismic processes reaching the Caspian Sea are distinctly registered by them. The conclusion is that when building networks of new stations, we must account for the fact that the sea is a perfect conductor for seismic-acoustic noises that appear during incipient ASPs in the region.

5. Following the experimental data, we can suggest that the lead time of the registration of ASP origin by a seismic-acoustic RNM ASP stations over standard seismic equipment is determined by two factors.

The first factor is that seismic-acoustic waves appearing at the start of an incipient ASP cannot reach the Earth's surface due to the frequency characteristics of some upper layers and spread instead horizontally as noise in deeper layers. When seismic waves reach the steel pipes of a well, they turn into acoustic signals and ascend at the velocity of sound to the surface to be caught by a hydrophone. Low-frequency seismic waves of seismic processes are registered by the receiving equipment of regular above-ground stations much later. By that time, an earthquake is already in progress.

The second factor is that with the use of noise technologies by analysing seismic acoustic noise, we can register incipient ASPs right at the start, as a correlation appears between the useful signal and the noise.

These two factors explain how RNM ASP stations are capable of indicating the time of the start of ASP origin so much earlier than the seismic survey service's above-ground stations.

6. Stations monitoring ASP can also monitor the hidden period of volcano formation well before a volcano erupts, or be used (on a regional scale) for testing minor and major nuclear bombs, as well as in assisting with other experiments related to the manufacture of military equipment.

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