PRECURSOR-BASED EARTHQUAKE PREDICTION: WISHFUL THINKING OR REAL POSSIBILITY?

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Abstract: Scientists attitude towards the delicate precursor-based earthquake prediction subject was widely oscillating during the last half century, from optimism to deep pessimism according to milestone seismic events, claims of successful predictions and published expert debate results. Despite the current official/mainstream opinion according to which the precursor-based earthquake prediction is impossible in principle, new ideas and claimed positive results emerged in the last few decades allowing potentially paradigm-shifting new research strategies to be envisaged and followed. Such a strategy is proposed here based on the principles of 1) coupled and interacting geospheres, 2) uniqueness of the seismic structures, hence of their precursory fingerprints, and 3) non-equivalence of Earth surface measuring sites from the perspective of signal-reception capability. Such a strategy aims at discovering the particular precursory fingerprint of individual seismogenic structures instead of looking for universally valid precursory signals. The precursory fingerprint of a particular seismogenic structure is the assemblage of a number of pre-seismic signals of physical, chemical and biological nature detectable in advance of impending large-magnitude earthquakes using a matrix of high-accuracy sensors emplaced at pre-selected "sensitive" locations at Earth surface and on Earth-orbiting satellites. It has a pattern component (configuration of the above-threshold values of the monitored parameters) and a time component (sequence, succession and lead time of emergence of the anomalous signal parameters). Due to its complex nature, the assemblage of detected precursory signals has to be processed and evaluated by pattern recognition algorithms of Artificial Intelligence systems and validated by human experts before final conclusions to be drawn. Due to its particular setting in Europe's geodynamically most active area, and its long-known seismic history including recurrent high-magnitude destructive events, the Vrancea seismic nest in Romania appears as an excellent experimental target for the implementation of a novel, concept-based long-term research strategy in the field of earthquake prediction.

Key words: earthquake prediction, precursory fingerprint, Vrancea seismic nest, research project.

Résumé : L'attitude des scientifiques à l'égard du sujet délicat de la prévision des tremblements de terre basée sur les précurseurs a largement oscillé au cours du dernier demi-siècle, allant de l'optimisme au profond pessimisme en fonction des événements sismiques marquants, des affirmations de prévisions réussies et des résultats publiés des débats d'experts. Malgré l'opinion officielle/l'opinion du grand public actuelle, selon laquelle la prévision des tremblements de terre basée sur les précurseurs est en principe impossible, de nouvelles idées et de prétendus résultats positifs ont émergé au cours des dernières décennies, permettant d'envisager et de suivre de nouvelles stratégies de recherche potentiellement révolutionnaires. Une telle stratégie est proposée ici basée sur les principes de 1) géosphères couplées et en interaction, 2) unicité des structures sismiques, donc de leurs empreintes précurseurs, et 3) non-équivalence des sites de mesure de la surface terrestre du point de vue de l'aptitude de la réception du signal. Une telle stratégie vise à découvrir l'empreinte précurseur particulière de structures sismogènes individuelles au lieu de rechercher des signaux précurseurs universellement valables. L'empreinte précurseur d'une structure sismogène particulière est l'assemblage d'un certain nombre de signaux pré-sismiques de nature physique, chimique et biologique, détectables avant l'imminence de séismes de grande ampleur, à l'aide d'une matrice de capteurs de haute précision placés à des endroits «sensibles» présélectionnés, emplacements à la surface de la Terre et sur des satellites en orbite autour de la Terre. Il comporte une composante de modèle (configuration des valeurs supérieures aux seuils des paramètres surveillés) et une composante temporelle (séquence, succession et délai d'apparition des paramètres du signal anormal). En raison de sa nature complexe, l'assemblage de signaux précurseurs détectés doit être traité et évalué par des algorithmes de reconnaissance de formes des systèmes d'intelligence artificielle et validé par des experts humains avant que des conclusions finales puissent être tirées. En raison de son emplacement particulier dans la zone géodynamiquement la plus active d'Europe et de son histoire sismique connue de longue date, y compris des événements destructeurs récurrents de grande ampleur, le nid sismique de Vrancea en Roumanie apparaît comme une excellente cible expérimentale pour la mise en œuvre d'une nouvelle stratégie de recherche à long terme dans le domaine de la prévision des tremblements de terre concept de longue durée basée sur des concepts.

Mots-clés: prévision des tremblements de terre, empreinte précurseur, nid sismique de Vrancea, projet de recherche.

1. INTRODUCTION

High-magnitude destructive earthquakes periodically trigger not only increased sensibility of state authorities and of the general public, but also media attention and coverage at local, regional and even global scale depending on the level of human lives loss and/or material damage caused by the seismic events, such as those occurred in the first half of 2023 in Romania, Oltenia (February 13, 14) and Banat, (June 6) regions following the catastrophic earthquakes at the Turkey/Siria boundary area in February 6. In such dramatic circumstances the extremely controversial subject of earthquake prediction is inevitably raised and addressed by social media agents and earth science scientists are insistently sought and interviewed in this respect.

This paper intends to address and review the problematic subject of deterministic, precursors-based earthquake prediction, its state-of-the-art status worldwide in general, and in Romania, in particular, to discuss the results obtained during the last few decades and to sketch a possible new approach of the subject. First, a retrospective of the ideas related to, and the attitude toward, the earthquake prediction problematics in the scientific community during the last half century is presented.

2. EVOLUTION OF THE IDEAS AND ATTITUDES RELATED TO PRECURSOR-BASED EARTHQUAKE PREDICTION

Here, we follow, retrospectively, how the ideas and attitudes within the earth science community have evolved in the last ca. 50 years with respect to the possibility of effective and workable earthquake prediction based on precursory signals.

One may observe a wild fluctuation of the degree of optimism related to this subject from sky-rocketing enthusiasm to deep pessimism and vice-versa as being strongly influenced by a number of milestone events in the science of seismology. Fig. 1 displays such a possible qualitative "curve of optimism" constructed based on the (more or less) subjective perception of the authors, as resulted from the professional literature of the subject through the last five decades. Next, we list and shortly discuss those evolutions and events having a crucial influence on how mainstream science addresses the issue of precursor-based earthquake prediction problematics.

1) The occurrence of the devastating February 4th $M_w7.3$ Haicheng earthquake in China was preceded by forceful evacuation of the local inhabitants of the area by the communist China's Army ordered by local state authorities warned by scientists on the basis of many unusual and

intriguing precursory phenomena including pre-shock seismic swarms, wild water level oscillations in pits and strange animal behaviour. Tens of thousands of lives were saved in this way, and the event was immediately claimed and promoted as the first successful earthquake prediction in the world and a triumph of Chinese science – and recognized as so by the scientific community worldwide (Wang *et al*., 2006). As a consequence, unprecedented optimism started to emerge from this story.

2) Roughly one and half year later, on July 28, the Tangshan earthquake in China claimed more than 240.000 victims as an aftermath of the Mw 7.6 seismic event (USGS, 2013) inducing the dramatic collapse of the "optimism curve" to an unprecedented low level. This time no relevant and convincing precursory signals occurred before the mainshock.
   Despite these two milestone events in the history of seismology, the major and common-sense lesson was not learnt, namely that there are no two identical earthquakes and no two identical seismogenic structures, hence no generally valid pre-earthquake precursor signals to be found and considered.
3) From the level of deepest pessimism, the "optimism curve" started to rise slowly during the following decades due to the experimentation and application of new investigation methodologies by a team of Greek scientists, known as the VAN method (from the initials of the three scientists) (Varotsos *et al*., 1986) by measuring the transient pre-seismic variations (anomalies) of the telluric electric currents. A series of published papers in high-impact scientific journals claiming relevant results and successful predictions (*e.g.*, Varotsos *et al*., 1986, Papadopoulos *et al*., 2018) inducing moderate optimism within the scientific community.
4) The published VAN-method results and claimed successful predictions triggered a decade-long debate in the 1990's known as the *Nature debate on earthquake prediction* during which the most prominent experts of the epoch in the domain expressed their findings and conclusions related to the VAN methodology. The final result of the debate was quite pessimistic culminating with the statement expressed as "*earthquakes cannot be predicted in principle"* because their intrinsic chaotic and nonlinear character (Geller, 1991, Geller *et al*., 1996, Mathews, 1997).
5) The ultra-sceptical outcome of the Nature debate (Main, 1999) was reinforced and then accepted as the prevailing and official paradigm (*e.g.*, by the USGS) after the publication of the volume entitled suggestively "*Predicting the unpredictable"* by USGS leading seismologist Susan Hough (Hough, 2010). As a consequence of these evolutions, the "optimism curve" descended again significantly to a second historical minimum.
6) Despite such discouraging evolutions, a series of scientists, in particular from countries most frequently hit by seismic disasters, did not give up trying to find innovative ways to address the precursor-based earthquake prediction puzzled by initiating investigations based on new principles and methodologies of research and by profiting from the technological advance and refinements in the domains of investigation tools, sensors and methodologies, including those held by man-made satellites. New and significant results started to be obtained and published. A milestone event of these evolutions is represented by the publication of the volume *The possibility of earthquake forecasting* (Pulinets and Ouzounov, 2018) in which a new paradigm-shifting approach is presented along with many encouraging research results obtained during the last few decades as synthetised by a number of authors from many countries, including successful predictions (mostly in a post-factum manner). The theoretical foundation of these new evolutions and results will be presented in the next section of this paper. Here we only mention that, as a result, the "optimism curve" started to rise again moderately as seen in Fig.1. It is to mention, however, that the sceptical attitude of part of the earth-science theorists and practitioners, seismologists in particular, remains unmodified, but their pessimistic

approach is not anymore the unique paradigm at stake today. A plethora of recently published research results, reviewed by Martinelli *et al*. (2021), seem to reinforce the more optimistic party of the science community and maintaining the "optimism curve" on its slightly ascending trend.

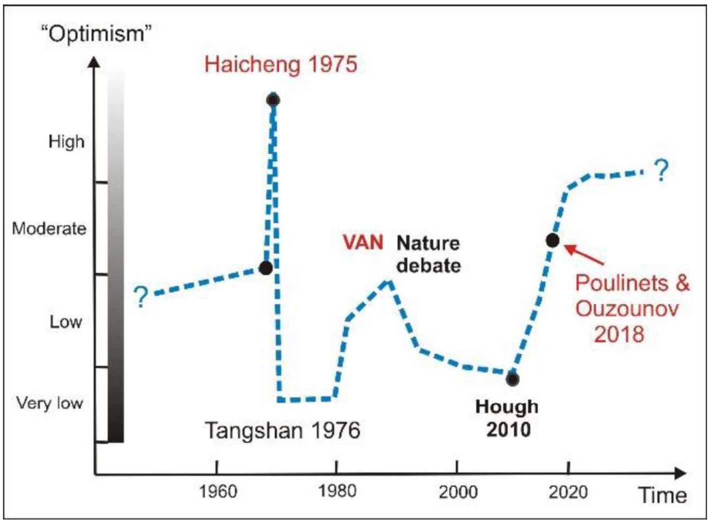

Fig. 1. Tentative graphical representation of the evolution of dominant attitudes of the research community related to the possibility of effective precursor-based earthquake prediction during the last ca. 50 years (explanation in the text)

In fact, the scientific community interested in the problematics of the precursor-based earthquake prediction issue is currently divided into two parties: a sceptical one (some of them radical) and an optimistic one (some more enthusiastic, others more moderate). The authors of this contribution shear the attitude of the latter group.

The sceptical investigators argue that at present there is no any well documented case of solid precursor-based earthquake prediction claimed, announced and sustained before the occurrence of a given seismic event and later validated by the occurrence of the event itself and by the expert community. Another argument brought into discussion is that most of the predictions claimed as being successful were, in fact, post-factum "predictions". That is true, but the lessons learnt from such post-predictions, validated post factum, may serve as precedents and can be valued in the newly envisaged investigation strategies.

3. THE CAUSES OF FAILURE OF EARTHQUAKE PREDICTION ATTEMPTS

Acknowledging that currently there is no any generally valid and largely acknowledged/accepted and reliable prediction methodology based on precursory signals, one may ask why all previous attempts to find universally valid precursors failed so far.

First, it is to note that using the word "lack of success" to characterize the state-of-the-art in this science domain is misleading because its relativity. In fact, there are a number of successful predictions as outcomes of the new wave of investigations, but 1) they are not always reported in peer-reviewed science journals, 2) not shared with authorities and/or the general public for prudential reasons, and 3) the prediction methodology is not generally applicable and valid.

With these statements in mind, one may consider the causes of the relative lack of success, other than "impossible in principle" (Wyss, 2001) as being due to 1) ambitious individual or small team attempts to solve the problem using self-devised methodologies and/or devices, *i.e.*, the lack interdisciplinary cooperation, 2) the lack of long-term innovative concept-based research strategies involving paradigm-shifting approaches at both national and international level, and 3) the lack of well-coordinated and adequately supported large-scale multidisciplinary international cooperation projects.

Next, we present a concept-based theoretical approach to the precursor-based earthquake prediction subject.

4. THEORETICAL AND CONCEPTUAL BACKGROUND OF A POSSIBLE PRECURSOR-BASED EARTHQUAKE PREDICTION RESEARCH STRATEGY

Although controversial, the existence of seismic precursory signals is generally accepted as valid, at least in theory, by the international science community (*e.g.*, Geller, 1991; Wyss, 2001). In theory, the sudden rupture in a rock volume produced in a seismogenic structure at the occurrence of a seismic event is preceded by the accumulation and escalation of stress and induced strain which, in turn, trigger certain modifications of the physical fields and of the chemical components of the surrounding solid (rocks) and fluid (liquids and gases) environment in the lithosphere. These modifications propagate outside the critical rock volume in the form of various geophysical and/or geochemical signals. Such signals can be recorded, in principle, at Earth surface by purposefully designated sensors adequately calibrated and located. Moreover, these modifications propagating through rocks in the lithosphere may trigger, by induction, further modifications in the other geospheres with which the lithosphere interacts in the form of secondary signals in the atmosphere and ionosphere, even in the magnetosphere, generated through complex interaction mechanisms (Pulinets *et al*., 2018, Hayakawa *et al*., 2018). As a consequence, one my rationally expect that a major seismic event on the brink of outbreak will be preceded by a number of primary and induced precursory signals of various nature (physical, chemical, biological).

Starting from the theoretical premises sketched above, we propose the following three principles to be considered as a possible conceptual basis for a precursor-based earthquake prediction research strategy.

4.1. THE PRINCIPLE OF COUPLED AND INTERACTING GEOSPHERES

This apparently banal and long-known principle in Earth sciences is an essential ingredient of any research strategy and it can be exploited in a new way from the perspectives of earthquake prediction. The principle of coupled and interacting geospheres was brought into the forefront of attention by Pulinets and Ouzounov (2018) who adopted this principle in their research strategy on atmospheric and ionospheric earthquake precursors using sensors on bord of artificial satellites.

The novel approach of these authors is based on the recognition of the integrated lithosphere-atmosphere-ionosphere system within which complex interactions and feedback mechanisms operate in the sense that events occurring in one of the components of this system will produce effects in its other components. In our case, a geodynamic event going on at the level of the lithosphere, in the crust or in the lithospheric mantle (both with a brittle rheology) preceding the occurrence of a major seismic event in the hypocentre will have consequences, say influences, in the other coupled interacting geospheres (hydrosphere, atmosphere and ionosphere, to which biosphere might be added) inducing changes in them, detectable in principle. The material agent of these interactions is the radioactive gas radon which, released from the rocks subjected to escalating pre-seismic stress regime in the earthquake preparation zone, and reaching the surface carried by carbon dioxide, will ionize the atmospheric air producing easily detectable thermal and humidity anomalies which, in turn, will induce further anomalies in the ionosphere. Such atmospheric and ionospheric anomalies appearing above the earthquake rupture zone can be detected by adequately devised satellite-held sensors.

Fig. 2, reproduced from Pulinets and Ouzounov (2018), presents the scheme of this system of coupled geospheres and the methodology of satellite-based detection of atmospheric and ionospheric anomalies produced by imminent seismic events together with their significant measurable parameters.

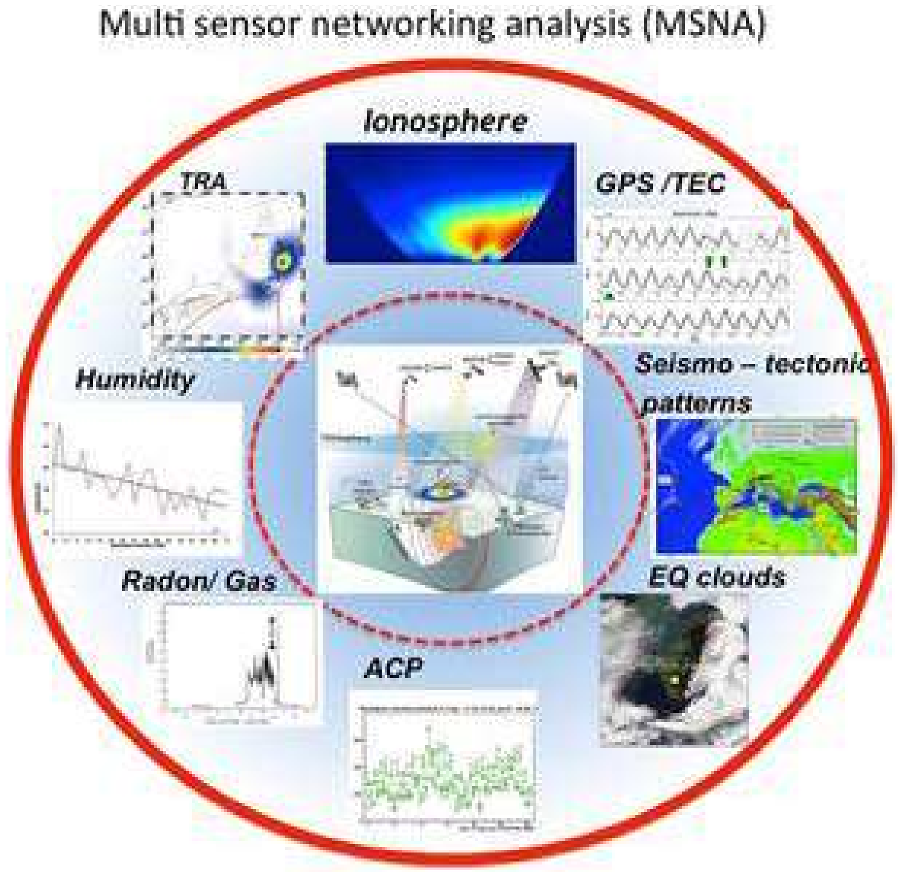

Fig. 2. Sketch of a multi-sensor precursory signal monitoring system based on the principle of coupled and interacting geospheres (acc. to Pulinets and Ouzounov, 2018).

This concept has the advantage of permitting the simultaneous monitoring of a various number of atmospheric and ionospheric parameters with satellite-held and ground-located instruments using multiple sensors, as well as of ground surfacer radon flux variations, the basic triggering factor of those anomalies.

A number of successful seismic predictions, mostly in post-prediction regime, using this concept and related methodology were reported and published in international science journals, as reviewed by Pulinets *et al*., 2018 and Martinelli *et al*., 2021. For example, Ouzonov *et al*, 2018 claim success in the validation of different anomalous pre-earthquake signals with a success rate of 21 out of 22 predictions.

It is to note that this prediction methodology based on the detection of atmospheric and/or ionospheric pre-shock anomalies claims that it has the ability to point out, with a certain accuracy, all three essential elements of a successful and acceptable prediction: place, time and magnitude category of the impending earthquake.

Another line of research based on the principle of coupled and interacting geospheres is based on the monitoring of Earth surface-emerging fluids (gases and liquids) which, in turn, may generate detectable anomalies of their characteristics such as flux and composition, related to major seismic event before, during and after those events. A review of this kind of investigations and their results was published by Martinelli and Dadamo (2018), Martinelli (2020).

The combined satellite- and ground-based monitoring of seismic areas yielded significant results in the domain of earthquake prediction research as stressed recently by Martinelli *et al.* (2020) claiming that *"part of the observed signals were detected before mainshocks"*.

These encouraging achievements and results obtained within the paradigm of coupled geospheres show, however, a major drawback: their claim of being universally valid and applicable. They are based on the implicit but unproved assumption that all seismogenic structures manifest themselves in a uniform manner during the earthquake preparation time period and, as a consequence, will produce the same (or, at least similar) set of precursory anomalies and signals to be pointed out by the used methodologies and instruments.

The meaningful lesson of the dramatic 1975–1976 Chinese seismic events is largely ignored. The wide diversity of seismogenic structures in terms of geodynamic setting, geological composition, depth, stress regime and focal mechanisms, and a number of other peculiar features making individual seismic structures unique, are also ignored. The handy conclusion to be drawn from this diversity suggesting that universally occurring precursors might not exist at all, was not considered at all.

4.2. THE PRINCIPLE OF UNIQUENESS OF THE SEISMIC STRUCTURES

Another common-sense observation is that seismogenic structures have a number of particular features making them different from any other structures. Their uniqueness is derived from the various geodynamic backgrounds and geological structures they belong to. Of course, typologies according to various criteria, such as hypocenter location (crustal and subcrustal) or depth (shallow, intermediate and deep), prevailing stress regime (compressional, dilatational, strike-slip), position in the global tectonics framework (plate boundary or intraplate), age of the hosting megastructure, and others might be identified. Within each of these categories individual seismogenic structures have, in turn, their own specific peculiarities due to which they are unique.

The acceptance of the principle of uniqueness of seismogenic structures has two major consequences. First, it is extremely unlikely that all seismogenic structures manifest themselves in the same manner in terms of precursory phenomenology. Foremost, it is very unlikely that all seismogenic structures behave identical before a major earthquake is unleashed, therefore one should not expect to see the same pre-shock warning signals in terms of type, number, intensity, timing, etc. of their manifestation. The lessons learnt after the two 1975–1976 Chinese megaseismic events are extremely relevant in this respect. From these statements results the uselessness of research strategies focused on the identification of universally valid seismic precursors.

Second, as derived from the above reasoning, the uniqueness of seismogenic structures involves also the uniqueness of the precursory phenomenology they produce. A particular seismogenic structure will generate a number of precursory signals specific only to that structure. The number of precursory signals may vary widely, from nil to a dozen. And they could be of physical, chemical and biological nature in a particular combination characterizing that unique structure. Therefore, the assemblage of specific precursory signals belonging to individual seismogenic structures can be viewed as the **precursory fingerprint** of that unique structure (Szakács, 2021).

From the perspective of earthquake prediction research, the major consequence of the approach sketched above is that investigation efforts have to be focused on individual seismogenic structures aiming at identification of their unique precursory fingerprint instead of searching for the Saint Grail of universal precursors.

4.3. THE PRINCIPLE OF NON-EQUIVALENCE OF EARTH SURFACE SPOTS FROM THE PERSPECTIVE OF SIGNAL-RECEPTION CAPABILITY

Seismic monitoring of a certain territory, such as the territory of a country, is commonly conducted through a sensor network emplaced in enough high number and as dense and uniformly distributed as possible sites for optimal coverage of that territory. Selection of emplacement locations also considers logistic criteria. Degree of territorial coverage is the most significant parameter taken into account. However, emplacement, operation and maintaining of such a network is also costly.

From the perspective of earthquake prediction research a different logic might work better, derived from the principle of non-equivalence of Earth surface sites as emplacement locations of monitoring equipment. According to this principle, one may find Earth surface spots which are more "sensible" than others from the perspective of signal reception capability, such as seismic precursory signals (physical, chemical, biological) generated in the interior of the lithosphere, propagated through geological structures until reaching the topographic surface (Szakács, 2011). In other words, deep-rooted geological structures as privileged transmission paths of seismic precursory signals, connecting their generation area and surface, may act as upside-down antennas or waveguides along which loss of energy and information is minimized as compared to any other possible crustal transmission paths. As a consequence, sensors emplaced at the intersection between such particular signal-transmission paths and surface will have the highest chance to record precursory signals of different nature with the most favourable possible signal-to-noise ratio.

Deep-rooted geological structures such as sub-vertical and steep trans-crustal fracture zones or faults, and conducts of extinct monogenetic volcanoes with deep-seated magma sources may be considered as favourable signal transmission paths (Szakács, 2011). It is easy to imagine that any information-bearing signal originating somewhere at depth in the lithosphere will propagate toward the surface much more efficiently along particular steep geological features with a simple structure or consisting of a more homogenous transmission medium (rocks) than along any other possible way through the structurally and petrographically heterogenous crust segmented by a plethora of sub-horizontal structural discontinuities and lithological boundaries.

Using a suggestive expression, such deep-rooted structures can be thought as "Earth chakras" through which the outward flux of matter, energy and information, from the planet's deep zones is focused and maximized.

The fact that there are more "sensitive" spots on Earth surface than others, as privileged fluids-carried chemical precursory signal reception sites was observed previously by researchers (*e.g.*, Martinelli and Dadamo, 2018).

The practical consequence of considering this principle is that any research aiming at identifying the precursory fingerprint of individual seismogenic structures involve previous geological and geophysical investigations purposefully focused on pointing out those peculiar geological structures and their corresponding "sensible" spots at surface, which represent the most favourable locations for emplacement of precursory signal detecting and monitoring equipment.

5. SKETCH OF A POSSIBLE PRECURSOR-BASED EARTHQUAKE PREDICTION RESEARCH STRATEGY

Starting from the postulate of rejecting the "impossible in principle" paradigm and from the principles discussed in the previous chapter, it is straightforward to sketch a coherent research strategy and project based on an innovative concept having a paradigm-shifting potential in the domain of earthquake prediction research. A proposal in this respect was already published by Szakács (2021). Next, we will present the outlines of such a strategy following that paper.

5.1. CONCEPT OF THE PROPOSED RESEARCH STRATEGY

The basic idea is that instead of trying to identify universally valid seismic precursor signals, a potentially successful strategy has to be focused on identifying the precursory fingerprint of individual seismogenic structures thus having merely a local validity, as an initial presumption. Precursory fingerprints have to be identified at as many as possible known seismogenic structures worldwide, ideally covering all types of geodynamic settings and stress regimes. Such a goal is achievable by selecting a number of well-known and thoroughly investigated seismogenic structures and monitoring them by observatories emplaced at "sensible" locations and adequately equipped by a large set of sensors of all types and with the highest possible sensitivity able to cover all possible types of precursory signals (seismic, physical, chemical, biological) to realize a multi-sensor and multiparameter monitoring system (Hayakawa *et al*., 2018), according to Fu and Lee (2018) who also argue for a *"systematic characterization of all possible precursors"*.

Taking into account that *"the majority of reported data during the last few decades related to seismic precursors proved to be of non-seismic nature (mostly electromagnetic"* (Hayakawa, 2018), the electromagnetic component of such a monitoring system should be well represented both by ground-emplaced and satellite-held sensors (as it is the current case of the French satellite DEMETER, Parrot and Li, 2018) in order to understand the mechanisms of lithosphere-atmosphere-ionosphere interaction at local scale (Hattori and Han, 2018, Hayakawa, 2018; Hayakawa *et al*., 2018). For example, pre-seismic atmospheric thermal anomalies are among those readily detectable by satellite-based sensors (Ouzounov *et al*., 2018; Tramutoli *et al*., 2018).

Based on literature data, Tramutoli *et al*. (2018) list a large spectrum of identified seismic precursors at various locations worldwide (in a post factum regime) which preceded large-magnitude earthquakes: topographic deformations, geochemical signals, thermal and infrared anomalies, anomalies of the atmospheric latent heat, temperature, humidity and pressure, VHF and VLF ionospheric signals, and others. Curiously, biological precursors are not mentioned. On the other hand, Martinelli (2020) stresses the importance of monitoring geofluids as carriers of seismic precursory signals and reviews the recent results of this kind of investigations including hydrogeologic measurements and chemical analyses of fluids (liquids and gases) emerging in seismic areas worldwide (China, Iceland, Japan, Russia, Taiwan, USA).

The data summarily presented above convincingly suggest that there is an abundant "offer" of virtual seismic precursory phenomena and a multitude of parameters (physical, chemical, biological, lithospheric, atmospheric, ionospheric) to be considered for research, evaluation and monitoring aiming at identifying the unique precursory fingerprint of individual seismogenic structures under scrutiny.

In such an approach one may realize a matrix of n (say 7×7 = 49) ground-based and satellite-held sensors operated at a research/monitoring station providing information in a continuous flux about the time-dependent variation of an even higher number of parameters (say 9×9 = 81) trying to detect seismic precursory signals and, implicitly, to identify the precursory fingerprint of the monitored individual seismogenic structure. Let's imagine that before an imminent seismic mainshock several (say 7 of the 49) of the sensors will be activated indicating a significant variation of a number (say 7 of the 81) of the measured parameters and, probably, only in the case of a certain threshold-passing magnitude value, also depending on the sensitivity of the respective sensors (Fig. 3). In such a way, the number and type of activated sensors and of the anomalous parameters, overpassing the pre-established threshold values, as well as their time sequence, may identify and characterize the precursory fingerprint of the investigated seismogenic structure generating that earthquake.

Experts in various categories of the monitored phenomena might evaluate the significance of overcoming those parameter threshold values and of the detected anomalies in order to distinguish real precursory signals from background noise.

Innovative Artificial Intelligence and Machine learning software using pattern recognition algorithms (*e.g.*, Shebalin *et al*., 2006, Rouen-Leduc *et al*., 2017) can be used as powerful tools to highlight complex but relevant correlations between various sensors (reactive and unreactive) and parameters (anomalous and not anomalous). For example, Boxberger *et al*. (2007) consider that *"Multi-parameter Wireless Sensing system allows different sensor types to be combined with high-performance computing and communication components."*

5.2. STAGES OF THE RESEARCH STRATEGY

Planning, implementation and realization of a research strategy related to precursor-based earthquake prediction has to consider a long-term run irrespective of where – in Romania or wherever worldwide – is initiated. Moreover, large-scale multi-institutional and international cooperation is a prerequisite of the envisaged successful outcome.

Such a long-term (*i.e.*, decades long) strategy needs three phases to be followed successively: 1) experimentation, 2) validation and extension, 3) implementation (Szakács, 2021). Each phase has particular goals and duration.

The main goal of the **experimentation phase** (or "learning phase", acc. to Peresan, 2018) is to test the validity of the precursory fingerprint concept by setting up (or use, where already available) of a few research observatories in the vicinity of selected seismogenic structures worldwide which are well-known, thoroughly studied and benefiting from a professional seismic surveillance system.

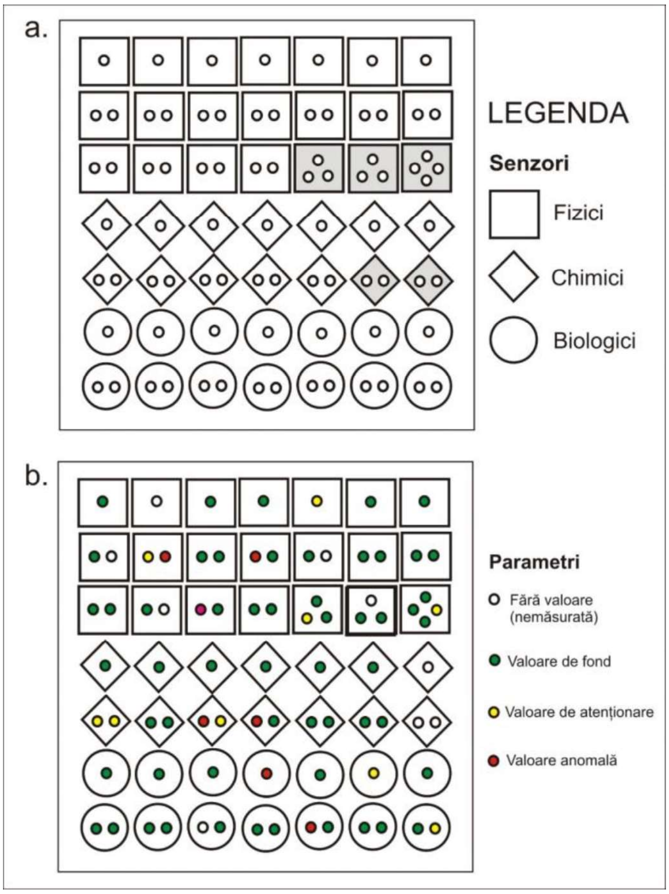

Fig. 3. Conceptual scheme of a matrix consisting of a multidisciplinary network of ground-based (white) and satellite-held (grey) sensors measuring a large number of parameters (small circles) of physical (square), chemical (diamond) and biological (large circle) nature (a); measured values of the monitored parameters are marked by colours (white; not measured), green: background value, yellow: threshold-close warning value, red: anomalous value) (b).

Each of them will be equipped with a matrix of sensors of as many as possible types (combined ground-based and remote sensing type, Sgrigna *et al*, 2007), following Birkhäuser's (2004) statement saying that *"progress in seismology and in the problematics of earthquake prediction during the next few decades claims the intensive monitoring of a few active seismic areas"*. The sensors aimed at recording precursory signals of all possible types would measure and monitor a large number of parameters of the physical fields simultaneously with monitoring the background seismicity using the existent network of seismic stations. Subtle changes of the physical (temperature, flux, turbidity) and chemical (dissolved ionic components, dissolved gases, soil gases, CO_2, CH_4, He, H, Hg, radon, thoron) properties of the fluids circulating in the crust and their time-dependent fluctuations will be monitored in parallel. Ground deformation and other virtual precursory signals which can be monitored using remote sensing technologies will complete the ground-based system. It will also include biological sensors to monitor the changing behaviour of living organisms before large seismic events as a response of the sensitive living matter to the pre-earthquake changes of their physical and chemical natural environment. All levels of organization of the living matter, from bacteria to primates, are to be investigated.

The experimental phase also requires innovative laboratory experiments in order to devise, develop and/or improve high-sensitivity and high-reliable sensors to be tested and evaluated in the monitoring observatories.

Another line of research in the experimental phase includes geological and geophysical investigations in order to identify the most adequate locations for equipment and sensor emplacement in those particular "sensible" Earth-surface spots where precursory signals arrive, at the end-point of their optimal propagation paths, with minimal loss of information energy. In this context it is worthy to mention the observation of Martinelli and Dadamo (2018) who, based on previous investigation results, state that geochemical and hydrogeological precursors were recorded in intervals ranging from hours to months before high-magnitude earthquakes at "sensible" monitoring sites besides many "insensitive" ones.

The duration of the experimental phase depends, mostly, on the seismic activity of the monitored structure: the occurrence of at least one major seismic event is necessary to evaluate the performance of the monitoring system and to find out whether the investigated seismogenic structure produces relevant precursory signals detectable by the installed sensor matrix or not. In other words: whether that seismogenic structure can or cannot be characterized by a particular precursor fingerprint pointed out by the used multidisciplinary and multi-sensor monitoring system.

In the most optimistic scenario, the expected result of the experimental phase would be a credible and effective methodology of identification of the precursory fingerprint of at least some of the investigated seismogenic structures. In the case of negative results at all monitored structures the research staff will judge, case by case, the opportunity of abandonment of the project or its continuation until at least the next major seismic event will occur.

The **validation/extension phase** will follow the experimental one only if it will be considered successful or, at least, with relevant and useful results obtained for further research work. The gained experience in the first phase will be valued through extension to investigate further seismogenic structures in order to 1) validate the positive results already obtained and 2) improvement and refinement of the multisensorial matrix at some of those selected structures where negative or inconclusive results were obtained, maintaining the monitoring system instead of its abandonment.

The duration of this phase will also depend on the occurrence of at least one major seismic event at the majority of the monitored structures.

The **implementation phase** will consider only those seismogenic structures where both previous phases concluded with positive results, namely where the precursory fingerprint was credibly and testably pointed out and characterized. As a result, a global network of operational multi-sensor observation stations will be established at a number of well-studied seismogenic structures, hopefully including those of the highest seismic hazard, whose precursory fingerprint was readily determined.

The multiparameter monitoring systems will be continuously rationalized and optimized by eliminating the inert (*i.e.*, non-responsive) sensors from the matrix. Instead, further effort of experimental investigation will be invested to increase the sensitivity of the remaining responsive sensors, to upgrade data acquisition, storage and processing tools at the stations where positive results were obtained, while the new results will be disseminated and implemented at all other existing monitoring stations.

5.3. THE VRANCEA SEISMOGENIC STRUCTURE AS AN ADEQUATE TARGET FOR EARTHQUAKE PREDICTION RESEARCH

The intermediate-depth (60–180 km) Vrancea seismic zone represents a well-individualized earthquake-generating nest, with an active high frequency background seismicity and recurrent large-magnitude (M_w>6.5) catastrophic events at decades-scale time intervals (Radulian *et al*, 2000). It is located at the external part of the East Carpathians bend zone within a lithospheric block bunded by two major NW–SE striking trans-crustal tectonic features: the Trotuș fault in the north and the Intra-Moesian fault in the south in an active geodynamic framework, the most dynamic one in the whole Carpathian-Pannonian Region. A number of recent and current geodynamic processes converge in space and time in this area. At the Carpathian bend exterior rollback, verticalization and detachment of a NW-ward subducted slab accompanied by uplift of the Vrancea Mts. and rapid active subsidence of the adjacent Focsani Basin are the major driving mechanisms in the area hosting the Vrancea seismogenic zone (Matenco and Bertotti, 2000, Tărăpoancă *et al.*, 2003). Further recent-to-present geodynamic processes are observed at the Carpathian bends internal part, such as the continuous SE-ward younging of dynamic topography in the Transylvanian Basin (Molin *et al.*, 2012), time-space migration of Neogene-Quaternary subduction-related volcanism in the SE direction in the whole Carpathian Pannonian Region, and more intensively along its East Carpathian volcanic range segment (Szakács *et al.*, 2018), the occurrence of Pleistocene mantle-source alkali basaltic volcanism in the Perșani Mts. (Seghedi *et al.*, 2016), abundance of deep-origin fluid-emergence surface spots in the form of dry or wet carbon dioxide emanations (*e.g.*, Vaselli *et al.*, 2002), location of the most recent (ca. 28.000 years ago, volcanic activity (*e.g.*, Karátson *et al.*, 2016), and occurrence of the most intense local geothermal anomaly (Demetrescu and Andreescu, 1994).

The occurrence of so many recent-to-active geodynamic processes, including active seismicity, in such a limited territory, qualifies the Carpathian bend area an adequate candidate as experimental target in the domain of precursor-based earthquake prediction research at national/regional or even global scale. In this respect unique and ideal conditions are met here since most, if not all, the mentioned geodynamic processes are inter-correlated within a unique and complex system allowing one to logically infer that stress accumulation and escalation in the Vrancea seismogenic nest influences at least some of the other components of this system. In other words, components of such a geodynamic system acquire, by mutual interactions, the property of being “sensible” to what is going on in the Vrancea seismogenic rock volume and, as a consequence, prone to modifications in the form of precursory “anomalies”, detectable in principle using adequate monitoring equipment.

Based on the theoretical/conceptual framework sketched in section 5.1., and profiting from the uniquely favourable conditions of the Vrancea seismic zone, a large-scale target-oriented research project can be initiated and promoted. The goal of the envisaged project would be the search for the precursory fingerprint of the high-magnitude Vrancea seismic events.

Actually, research work is currently going on with limited and currently exhausting resources within the framework of the Topo Transylvania project (Matenco, 2018), whose achievements can be viewed as the initial preliminary steps already done which can easily be integrated in the proposed larger project. An Integrated Geodynamic Station was emplaced and is currently working at Covasna supplying a continuous flux of data on the variation of diffusely emanating carbon dioxide concentration in soil gas and in the atmosphere. Too, focused carbon dioxide concentration variations are monitored in a mofette in the same locality, where months-long time series are already recorded intermittently during the last two years. A profile of 5 InSAR reflectors is planned to be installed in 2023 across a major fracture zone controlling gas emanations at Covasna in order to monitor possible topographic displacements using space geodetic remote sensing technology. Although planned and realized under a long-term strategic conception, these important steps already done are far insufficient and need to be followed and extended by further steps in order to realize that complex interdisciplinary multisensor/multiparamater monitoring system able to identify the precursory fingerprint of the Vrancea seismic zone. This goal should be attained before the occurrence of the next major seismic event in Vrancea.

Cooperating institutional and international partners and funding resources are sought. The sketch of a national project in this sense is currently being elaborated.

6. CONCLUSIONS

Following the evolution of ideas and attitudes (*i.e.*, optimistic versus sceptical) during the last half of century related to the possibility of earthquake prediction based on precursory signals an oscillating “optimism curve” can be traced. Although the pessimistic attitude seems to be still prevailing today, a new wave of encouraging research results may shift the balance in favour of a more optimistic approach of the problem. Recognition and consideration of the coupled and complexly interacting lithosphere-atmosphere-ionosphere system in earthquake prediction research allowed successful predictions (mostly in post factum mode) by using satellite-held remote sensing equipment revealing pre-seismic atmospheric and ionospheric anomalies. The claim of universal applicability of this seismic prediction methodology is the week point of this approach.

A more realistic research strategy can be envisaged based on the principle of coupled geospheres completed with the principle of the uniqueness of seismogenic structures and their precursory behaviour, and the principle of non-equivalence of Earth surface spots in terms of their sensitivity to precursory signals. Such a strategy aims at discovering the particular precursory fingerprint of individual seismogenic structures. The precursory fingerprint of a particular seismogenic structure is the assemblage of a various number of pre-seismic signals of physical, chemical and biological nature detectable in advance of impending large-magnitude earthquakes. It has a pattern component (configuration of the above-threshold values of the monitored parameters recorded by a matrix of sensors) and a time component (sequence, succession and lead time of emergence of the anomalous parameter values). Due to its complex nature, the assemblage of detected precursory signals has to be processed and evaluated by pattern recognition algorithms of Artificial Intelligence systems, then validated by human experts before final conclusions to be drawn.

The Vrancea seismic nest in the Carpathian’s bend area in Romania appears as one of the mot adequate targets for precursor-based earthquake prediction research due to its location in a geodynamically active region hosting many time-space converging coupled and interacting components of a currently active complex system within a well-outlined and a geographically limited area. This particularly favourable circumstance allows for a concept-based research strategy to be undertaken on precursor-based earthquake prediction with potentially international relevance in the science of seismology and in the broader Earth sciences in general.

The initial steps already done with encouraging results need to be followed and completed by further investigation efforts within the same strategic approach. Large-scale cooperation and proper financial and logistical support are prerequisite of the final successful completion of the project.

REFERENCES

Birkhäuser, B. (2004). Rethinking earthquake prediction. Pure Appl. Geophys. 155 (2–4), 207–232. doi:10.1007/978-1-4020-4399-4_106.

Boxberger, T., Fleming, K., Pittore, M., Parolai, S., Pilz, M., and Mikulla, S. (2017). The multi-parameter wireless sensing system (MPwise): its description and application to earthquake risk mitigation. Sensors. 17, 10. doi:10.3390/17102400.

Demetrescu, C., Andreescu, M. (1994) On the thermal regime of some tectonic units in a continental collision environment in Romania. Tectonophysics, 230, 3–4, 28, 265–276, https://doi.org/10.1016/0040-1951(94)90140-6.

Fu, Ch.-Ch., and Lee, L.-Ch. (2018). Continuous monitoring of fluid and gas geochemistry for seismic study in Taiwan. in Pre-earthquake Processes. A multidisciplinary approach to earthquake prediction studies. Editors D. Ouzounov, S. Pulinets, K. Hattori, and P. Taylor (John Wiley & Sons), 199–218.

Geller, R. J. (1991). Unpredictable earthquakes. Nature. 353, 612.

Geller, R. J., Jackson, D. D., Kagan, Y. Y., and Mulargia, F. (1996). Earthquakes cannot be predicted. Science. 275, 5306, 1616. doi:10.1126/science.275.5306.1616

Hattori, K., and Han, P. (2018). "Statistical analysis and assessment of ultralow frequency magnetic signals in Japan as potential earthquake precursors," in Preearthquake processes. a multidisciplinary approach to earthquake prediction studies. Editors D. Ouzounov, S. Pulinets, K. Hattori, and P. Taylor (JohnWiley & Sons), 229–240.

Hayakawa, M., Asano, T., Rozhnoi, A., and Solovieva, M. (2018). "Very-low- to low-frequency sounding of ionospheric perturbations and possible association with earthquakes," in Pre-earthquake processes. a multidisciplinary approach to earthquake prediction studies. Editors D. Ouzounov, S. Pulinets, K. Hattori, and P. Taylor (John Wiley & Sons), 277–304.

Hough, S. (2010). Predicting the unpredictable. The tumultuous science of earthquake prediction. Princeton: Princeton University Press, 280.

Karátson, D., Wulf, S., Vereș, D., Magyari, E.K., Gertisser, R., Timar-Gabor, A., Novothny, Á., Telbisz, T., Szalai, Z. (2016). "The latest explosive eruptions of Ciomad (Csomád) volcano, East Carpathians – A tephrostratigraphic approach for the 51–29 ka BP time interval". Journal of Volcanology and Geothermal Research, 319, 29–51, doi:10.1016/j.jvolgeores.2016.03.005.

Main, I. (1999b). Earthquake prediction: concluding remarks. Nature. doi:10.1038/ nature28133

Martinelli, G. (2018). "Contributions to a history of earthquake prediction research," in Pre-earthquake processes. a multidisciplinary approach to earthquake prediction studies. Editors D. Ouzounov, S. Pulinets, K. Hattori, and P. Taylor (John Wiley & Sons), 67–76.

Martinelli, G. (2020). Previous, current, and future trends in research into earthquake precursors in geofluids. Geosciences. 10, 189. doi:10.3390/geosciences10050189.

Martinelli, G., and Dadomo, A. (2018). "Geochemical and fluid-related precursors of earthquakes: previous and ongoing research trends," in Pre-earthquake processes. A multidisciplinary approach to earthquake prediction studies. Editors D. Ouzounov, S. Pulinets, K. Hattori, and P. Taylor (John Wiley & Sons), 219–228.

Martinelli, G., Facca, G., Genzano, N., Gherardi, F., Lisi, M., Pierotti L., Tramutoli V. (2020) Earthquake-Related Signals in Central Italy Detected by Hydrogeochemical and Satellite Techniques. Frontiers in Earth Science 8:584716, DOI: 10.3389/feart.2020.584716.

Martinelli, G., Peresan, A., Li, Y. (2021) Editorial: Achievements and new frontiers in research oriented to earthquake forecasting. Front. Earth Sci., Sec. Solid Earth Geophysics, Volume 9, https://doi.org/ 10.3389/feart.2021.793911.

Matenco, L., Bertotti, G. (2000) Tertiary tectonic evolution of the external East Carpathians (Romania), Tectonophysics, 316, 255–286.

Matenco L. (2018) Topo Transylvania: a multidisciplinary Earth science initiative in Central Europe to tackle local and global challenges, Acta Geodaetica et Geophysica, https://doi.org/10.1007/s40328-018-0234-z.

Matthews, R. A. J. (1997). Decision-theoretic limits on earthquake prediction. Geophys. J. Int. 131 (3), 526–529. doi:10.1111/j.1365-246X.1997.tb06596.x.

Molin, P., Fubelli, G., Nocentini, M., Sperini, S., Ignat, P., Grecu, F., Dramis, F. (2012) Interaction of mantle dynamics, crustal tectonics, and surface processes in the topography of the Romanian Carpathians: A geomorphological approach. Global and Planetary Change, 90–91, 58-72, https://doi.org/10.1016/j.gloplacha.2011.05.005.

Ouzounov, D., Pulinets, S., Liu, J.-Y.,Hattori,K., andHan, P. (2018b). "Multiparameter assessment of pre-earthquake atmospheric signals," in Pre-earthquake processes: a multidisciplinary approach to earthquake prediction studies. Editors D. Ouzounov, S. Pulinets, K. Hattori, and P. Taylor (John Wiley & Sons), 339–359.

Papadopoulos, G., Minadakis, G., and Orfanogiannaki, K. (2018). "Short-term foreshocks and earthquake prediction," in Pre-earthquake processes: a multidisciplinary approach to earthquake prediction studies. Editors D. Ouzounov, S. Pulinets, K. Hattori, and P. Taylor (JohnWiley & Sons), 127–147.

Peresan, A. (2018). "Recent developments in the detection of seismicity patterns for the Italian region," in Pre-earthquake processes. a multidisciplinary approach to earthquake prediction studies. Editors D. Ouzounov, S. Pulinets, K. Hattori, and P. Taylor (John Wiley & Sons), 149–171.

Pulinets, S., Ouzounov, D., Karelin, A., and Davidenko, D. (2018). "Lithosphere–atmosphere–ionosphere–magnetosphere coupling—a concept for pre-earthquake signals generation," in Pre-earthquake processes: a multidisciplinary approach to earthquake prediction studies. Editors D. Ouzounov, S. Pulinets, K. Hattori, and P. Taylor (John Wiley & Sons), 79–98.

Radulian, M., Mandrescu, N., Panza, G. F., Popescu, E., Utale, A. (2000). Characterization of seismogenic zones of Romania. Pure Appl. Geophys. 157, 57–77. doi:10.1007/PL00001100.

Rouet-Leduc, B., Hulbert, C., Lubbers, N., Barros, K., Humphreys, C. J., and Johnson, P. A. (2017). Machine learning predicts laboratory earthquakes. Geophys. Res. Lett. 44, 9276–9282. doi:10.1002/2017GL074677.

Seghedi, I., Popa, R.-G. Panaiotu, C. G., Szakács, A., Pécskay, Z. (2016) Short-lived eruptive episodes during the construction of a Na-alkalic basaltic field (Perşani Mountains, SE Transylvania, Romania). Bull Volcanol, 78:69, DOI 10.1007/s00445-016-1063-y.

Sgrigna, V., Buzzi, A., Conti, L., Picozza, P., Stagni, C., and Zilpimiani, D. (2007). Seismo-induced effects in the near-earth space: combined ground and space investigations as a contribution to earthquake prediction. Tectonophysics. 431 (1–4), 153–171. doi:10.1016/j.tecto.2006.05.034.

Shebalin, P., Keilis-Borok, V., Gabrielov, A., Zaliapin, I., and Turcotte, D. (2006). Short-term earthquake prediction by reverse analysis of lithosphere dynamics. Tectonophysics. 413, 63–75. doi:10.1016/j.tecto.2005.10.033.

Szakács, A. (2011) Earthquake prediction using extinct monogenetic volcanoes: a possible new research strategy. J. Volcanol. Geotherm. Res. 201, 404–411. doi:10. 1016/j.jvolgeores.2010.06.015.

Szakács, A. (2021) Precursor-Based Earthquake Prediction Research: Proposal for a Paradigm-Shifting Strategy. Front. Earth Sci., Sec. Geohazards and Georisks, Volume 8, 2020, https://doi.org/10.3389/feart.2020.548398.

Szakács, A., Pécskay, Z., Gál, Á. (2018) Patterns and trends of time–space evolution of Neogene volcanism in the Carpathian–Pannonian region: a review. Acta Geodaetica et Geophysica, 53, 347–367.

Tarapoanca, M., Bertotti, G, Matenco, L. C., Dinu, C., Cloetingh S. (2003) Architecture of the Focsani Depression: A 13 km deep basin in the Carpathians Bend Zone (Romania). Tectonics, 22(6):13-1 DOI: 10.1029/2002TC001486.

Tramutoli, V., Filizzola, C., Genzano, N., and Lisi, M. (2018). "Robust satellite techniques for detecting preseismic thermal anomalies," in Pre-earthquake processes: a multidisciplinary approach to earthquake prediction studies. Editors D. Ouzounov, S. Pulinets, K. Hattori, and P. Taylor (John Wiley & Sons), 243–258.

U.S. Geological Survey (2013). Earthquakes with 50,000 or more deaths. Archive. Available at: http://earthquake.usgs.gov/earthquakes/world/most_destructive.php.

Varotsos, P., Alexopoulos, K., Nomicos, K., and Lazaridou, M. (1986). Earthquake prediction and electric signals. Nature. 322, 120. doi:10.1038/322120a0.

Vaselli, O., Minissale, A., Tassi, F., Magro, G, Seghedi, I., Ioane, D., Szakacs, A. (2002) A geochemical traverse across the Eastern Carpathians (Romania): constraints on the origin and evolution of the mineral water and gas discharges,182, 2–4, 637–654.

Wang, K., Chen, Q. F., Shihong, S., and Wang, A. (2006). Predicting the 1975 Haicheng earthquake. Bull. Seismol. Soc. Am. 96 (3), 757–795. doi:10.1785/0120050191.

Wyss, M. (1997). Second round of evaluations of proposed earthquake precursors. Pure Appl. Geophys. 149, 3–16. doi:10.1007/BF00945158.

Wyss, M. (2001). Why is earthquake prediction research not progressing faster? Tectonophysics. 338 (3–4), 217–223. doi:10.1016/S0040-1951(01)00077-4.