



Original paper

Earth observation capacity of the National Geoinformation Center of Bulgaria as Part of the Tools for Geo- and Anthropogenic-Hazard Management in EPOS

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Abstract Exploring the nature of the Earth system and its multi-scale architecture requires an integrated symbiotic approach not only to understand our planet but also to reveal the hazards and footprints of their events on human life. Following the conceptual model of the European Plate Observing System (EPOS) we integrate a variety of research to obtain a multilateral use of geoinformation for scientific and practical purposes. In 2018, we started building a Bulgarian distributed scientific infrastructure called the National Geoinformation Center, aiming to provide data, products, and expertise to predict and prevent natural and anthropogenic risks and disasters, as well as environmental changes.

The present paper demonstrates the capabilities of seismological, Global Navigation Satellite System (GNSS), geomagnetic and multi-scale laboratories (MSL) in Bulgaria that participate to the respective thematic core services of EPOS. More than 40 seismological stations register and transmit data in real time through the operational center of the Bulgarian Seismological Network. Data from 18 GNSS stations, part of the National GNSS network, are officially registered in the EPOS GNSS Data Gateway. Data and products are available via the EPOS GNSS Product Portal for interested users. Panagjurishte geomagnetic observatory (PAG) provides real time variations and long-period data series for the Earth's magnetic field. The Palaeomagnetic Laboratory at the National Institute of Geophysics, Geodesy and Geography (NIGGG) participates in MSL with its unique facilities for paleo-, archeo- and environmental magnetism studies.

Four case studies are presented to illustrate best practices for utilizing the data collected. The analysis of seismicity in a region of a long-time exploited salt deposit is upgraded with GNSS

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data to reveal the reason for crustal movements in the region. The results show that the majority of the seismic events took place in the upper part of the Earth's crust at a depth of up to 5 km, where the salt body is buried. The observed significant local deformations of the Earth's surface are very likely related to the technological process of deposit exploitation.

A recent model of the geomagnetic declination over the Bulgarian territory is also presented. It tracks the variation of the regional magnetic field from 2015 to 2020 and adds short-wavelength signals from the secular network observations. Last but not least, the application of a mineral magnetic laboratory analysis along the depth of a Holocene soil profile is demonstrated. Results reveal the soil evolution in response to environmental changes adding a new magnetic proxy parameter for more precise identification and characterization of the soil formation processes.

Keywords: National geoinformation center, Bulgaria, seismological data, GNSS data, geomagnetic data, paleomagnetic laboratory, EPOS

1. INTRODUCTION

NGIC, the National Geoinformation Center of Bulgaria, is a multidisciplinary, distributed research infrastructure that facilitates the integrated use of data, data products, and services. With its Earth observation capacity, NGIC participates in four of the thematic core services of the European Plate Observing System (EPOS) - the largest solid Earth science community in Europe.

The overall mission of this research infrastructure is to reduce the impact of natural disasters and industrial accidents establishing a sustainable and long-term access to solid Earth science data and services. Besides fostering state-of-the-art research and innovation, we develop services that might be used directly by the national authority for decision-making processes and others to educate and raise public awareness about disaster prevention and adequate reaction.

In this paper we showcase the technical capabilities of the NGIC research infrastructure and present one example of best practices in each of the four thematic cores of the EPOS which are connected to disaster prevention and management, and environmental changes. These studies involve high-level scientific investigations which are dedicated to solve vital problems of society and the economy using modern and high-quality Earth observation data and methods.

The first two case studies investigate the manifestation of local seismicity and geodetic deformations near an industrial site for salt deposit exploitation in northeastern Bulgaria. The Mirovo salt deposit has been in operation for more than 60 years, and the salt is obtained by leaching salt solution on the surface. As a result of the long period of salt extraction, the natural balance of the salt body and the surrounding rocks appears to be disturbed, the risk of tectonic earthquakes and technogenically induced seismicity has increased. Recent studies by Paskaleva

et. al (2010) and Dimitrova *et al.* (2015) confirmed that the analyzed response spectra show maxima of the prevailing periods – 0.08 to 0.23 sec for the horizontal ones and 0.05 to 0.23 for the vertical ones. Such a frequency composition, full of high-frequency oscillations, is characteristic of small epicentral distances of realization which direct attention to the local seismicity. The ratio of the maximum horizontal to the maximum vertical acceleration 0.17-2.26 confirms the realized earthquakes' local nature and the vertical component's predominant influence. Yankova and Dimovski (2015) evaluated the reservoir properties of thick terrigenous rocks in the region providing a thorough description of the local tectonic structures and fault localization. They describe eight fault structures that chronostratigraphically encompass deposits belonging to the Permian, Triassic and Jurassic systems. Only at one of the fault structures, located to the east of the salt body, traces of activity from the Paleozoic to the present stage can be observed, with different amplitudes in the individual structural layers. This fact also supports the hypothesis of a lack of tectonically activated seismicity in most cases and motivates the analysis presented in this paper (Section 3.1).

In order to enhance the seismicity study, an assessment of the geodetic deformations is also made. A recently published analysis of the wide-region GNSS data (Kenyeres *et al.* 2019) shows a horizontal velocity of less than 1 mm/year for northeastern Bulgaria (including the studied territory) and vertical velocities with similar values from which might be concluded that the general subsidence is primarily due to sediment compaction. The tectonic strain field obtained from horizontal velocities demonstrates very small extension approximately in the NE–SW direction (Shanov 2005; Solakov *et al.* 2019).

Previous results from local zone investigation including periodic geodetic measurements and DInSAR interferograms show horizontal and vertical movements and deformation processes of the Earth's crust, resulting in shrinkage, stretch, sinking, tilting (Atanasova and Nikolov, 2016). Displacement with magnitude of 5 to 6 mm/y have been reported from the satellite based technique. An additional assessment of the surface subsidence along with analyses of the seismic regime variation for the area of Mirovo salt deposit is presented in this research (Section 3.2).

The next two case studies shift the focus from deformations of the Earth's crust to the study of phenomena by means of measuring and modeling the geomagnetic field.

Global geomagnetic field models, are usually computed from spherical harmonic series and are becoming of increased importance for understanding processes such as magnetic field generation, jerks or polarity reversals. On the other hand, a regional numerical model of sufficient complexity, including adequate secular variation correction, provides a suitable representation of the regional field and might be used for topographic mapping and reduction of all magnetic survey data. A series of models of the main geomagnetic field exist for Bulgaria: from the era of analogue observatory data registration for 1960.0, 1965.0, 1970.0 epoch (Buchvarov and Kostov, 1981), for 1980.0 (Kostov *et al.*, 1991) and for 1990.0 (Buchvarov and Cholakov, 1994) up to the new model for 2015.0 epoch called BulGRF (Metodiev and

Trifonova, 2017). The last one, characterized by a set of six coefficients for each field element, was produced by least-squares fitting of a second-degree polynomial of geographical coordinates to 473 points over the territory of Bulgaria. Values of the BulGRF 2015.0 coefficients were obtained using the least-squares regression method. The self-consistency of the model was checked upon the geometrical constraint (Haines, 1990) and with the latest version of CHAOS and CHAOS-6, as it covers the time period 1999 to 2016.5 (Finlay *et al.*, 2016) and the latest edition of IGRF model (Thébault *et al.*, 2015).

In this paper, the last updated to 2020.0 epoch model is presented, which includes the most recent data from nearby observatories and Bulgarian repeat stations, thus producing a much better spatial resolution of the magnetic field variations (Section 3.3).

The last example of experimental research, conducted by using the upgraded laboratory equipment at NGIC, aims to strengthen the understanding of the build up of soil magnetic signature. The latter is of prime importance for the application of correlative age modelling techniques in sedimentary loess – paleosol sequences and dating of deposits older than the possibilities of existing techniques (Constantin *et al.*, 2021). A key question need to be addressed in this respect is the presence of continuous dust sedimentation not only during the cold glacial periods but also during the warm interglacials. These issues were discussed in previous papers (Varga, 2015; Rousseau *et al.*, 2017), but new methods for identification and characterization of changing sedimentary environments are still needed. A recently published paper by Jordanova and Jordanova (2020) proposed new magnetic proxy method for evaluation of the existence or absence of dust additions during soil formation. The presented here study upgrades this methodology by adding new magnetic proxy parameter – viscous remanent magnetization (Section 3.4). It is shown that using this new property in combination with other magnetic grain size sensitive parameters allows even more precise identification and characterization of the soil forming environment.

2. TECHNICAL CAPACITY

2.1 Seismological Network

The seismological network of the National Operational Telemetric System for Seismological Information consists of 41 seismic stations, including two Local Seismological Networks (LSN) nearby the Nuclear Power Plant (NPP) “Kozloduy” and close to the Provadiya salt mine. They are equipped with 3-component broadband seismometers, with responses ranging from 50 Hz to: 30s, 60s, 120s and 360s and in most stations - accelerometers (Fig. 1). Seismic data are digitized by Reftek DAS 130 and Bazalt Digital Systems and transferred to the Data Centre via VPN. The real-time seismic data are implemented by the automatic data processing software using two protocols – RTPD and SeedLink. SeedLink protocol is also used for data exchange with the seismic centers of the neighboring countries and various International Data Centers.

Initially, Seismological Data Center is equipped with SNDP (Seismological Network Data Processor) software delivered by Reftek Inc., together with seismological equipment for the monitoring stations. The main task of SNDP is automatic data processing and obtaining rapid information about earthquakes. To improve Data Center capacity, the advanced SeisComPro software was installed recently. Gempa (<https://gempa.de>) developed this software for automatic real-time data processing and fast post-processing. Three commercial SeisComPro modules, implemented in the Center's routine practice, monitor natural and induced seismicity, produce a better estimate of event locations, and calculate and analyze moment tensors. In routine practice, the main parameters of the earthquakes are estimated using the DHypo computer code (Solakov, 1993).



Figure 1. Seismological equipment of a standard monitoring seismic station consisting of (a) data logger, (b) three-component seismometer located in the black heat-insulating cover, (c) accelerometer and d) network communication module. There are also a museum exhibit of SM-2M short-period, single-component seismometer (e).

The input information for calculation of the earthquake parameters is the P and/or S onsets, the maximum amplitude of the P and/or S phases and/or signal duration. Produced bulletins are used for subsequent catalog compilation.

A real-time data exchange with international (MEDNET <http://terremoti.ingv.it>, ORFEUS-European Center for Digital Seismological Data- <https://www.orfeus-eu.org>, NEIC - <https://www.usgs.gov>, etc.) and regional seismological centers (Romania, Turkey, Greece, Serbia, North Macedonia, Ukraine, etc.) is established. Seismological information is sent to the international data centers EMSC (<http://www.emsc-csem.org>) and ISC (<http://www.isc.ac.uk>). NIGGG is a national data center within Comprehensive Nuclear Test-Ban Treaty Organization (CTBTO).

2.2 Permanent GNSS Network

The National Permanent GNSS (Global Navigation Satellite Systems) Network (Fig. 2) consists of more than 20 permanent GPS/GNSS stations where data are archived, processed and analyzed in the Data center. Results from the analyzed GNSS data consist of: 1) temporary lines with the coordinates of the permanent stations; 2) high-precision coordinates of the permanent GNSS stations; 3) velocities of permanent GNSS stations.

The results are used to monitor the modern movements and stresses of the Earth's crust on the territory of the country, the Balkan Peninsula, and the Eastern Mediterranean, as well as to assess the seismic hazard. They are also an essential component of the maintenance of the State GPS network of the Republic of Bulgaria.

The Data center is the Operational Center for the analysis of the European permanent GNSS network in its densification activities (European project EUREF Permanent Network Densification), whose main task is to build a homogeneous and high-precision network of permanent GNSS stations in continental Europe.

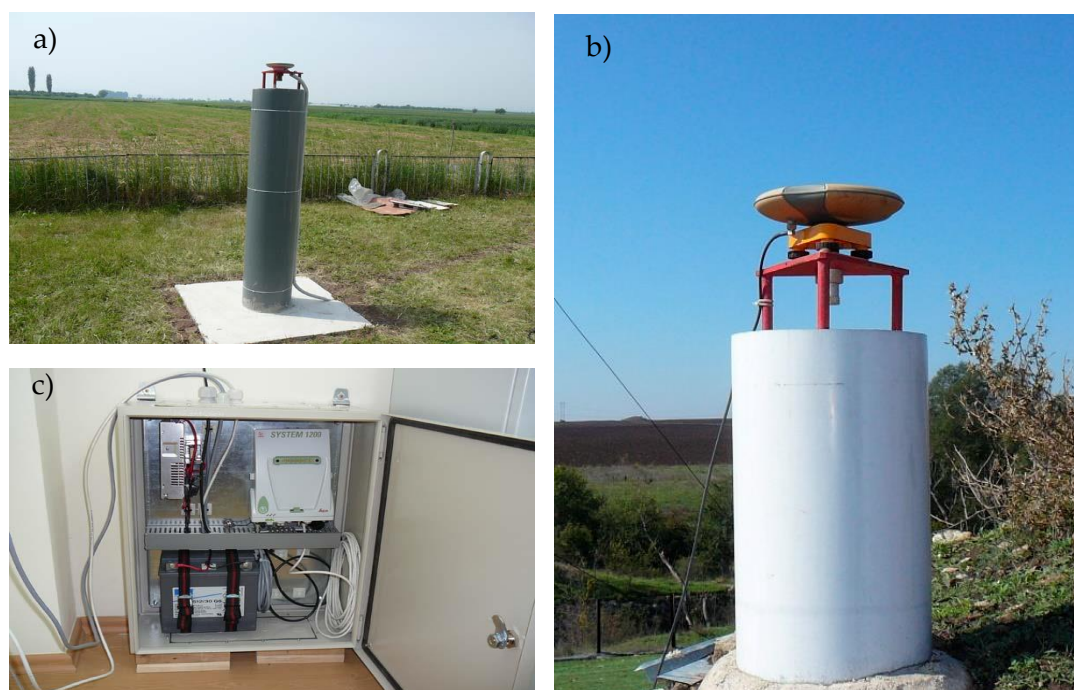


Figure 2. Permanent GNSS stations (GPS antennas in (a) Pazardzik, PAZA and (b) Provadia, PROV) stabilized on reinforced concrete posts and (c) electronic block for data transmission.

2.3 Geomagnetic Observatory Panagjurishte

The contribution of NGIC to the TC Geomagnetic observation is also significant. The most important facility is the Panagjurishte Observatory (Fig. 3) which was set into operation in 1937. All observatory buildings are constructed carefully using materials tested for magnetic properties (Fig. 3).

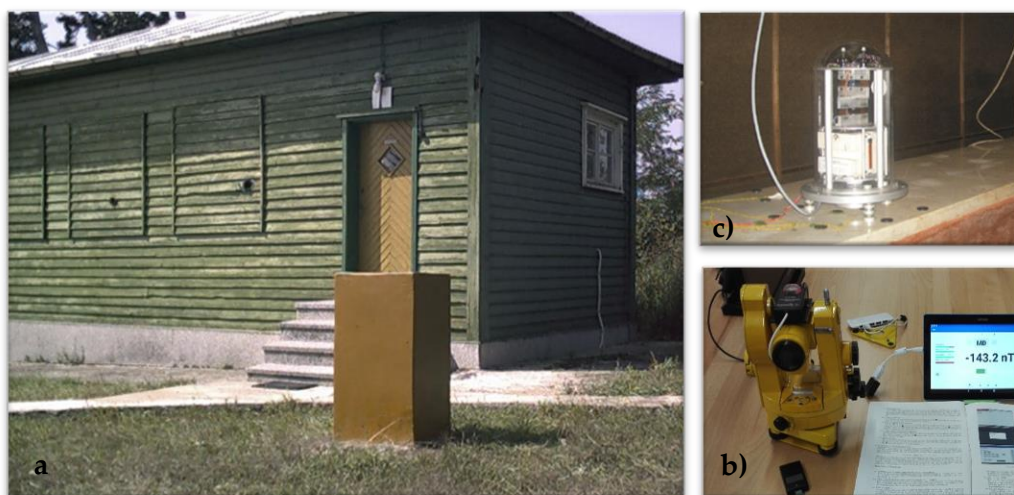


Figure 3. Absolute house of the PAG observatory (a) and the main equipment – non-magnetic theodolite with fluxgate magnetometer (b) and three-axial vector magnetometer FGE (c)

The relative house is dug into the ground at approximately 2 m depth and has a very good temperature isolation with an annual variation less than 2°C.

In the observatory, three different magnetometers are installed which operate in 24/7 regime: two tri-axial fluxgate magnetometers model FGE (DTU Space) – one of standard and one of suspended version. The third instrument is a three-axial search coil magnetometer used for studies on propagation of ULF signal which provides real time measurements with a frequency of 100 Hz.

2.4 Paleomagnetic Laboratory

NGIC participation in the Multiscale Labs thematic core of EPOS is represented by the Paleomagnetic laboratory. The main topics of its monitoring and scientific research are soil and environmental magnetism, as well as archeomagnetic investigations. Researchers work with modern specialized equipment for palaeomagnetic studies such as automatic spinner magnetometer, alternating-field (AF) demagnetizers, shielded furnace, kappa bridge, sieving machine, magnetic separator, *etc.* (Fig. 4). In addition to equipment for laboratory research, the team also uses equipment for field measurements, as for example kappa meters for in situ measurement of the magnetic susceptibility.

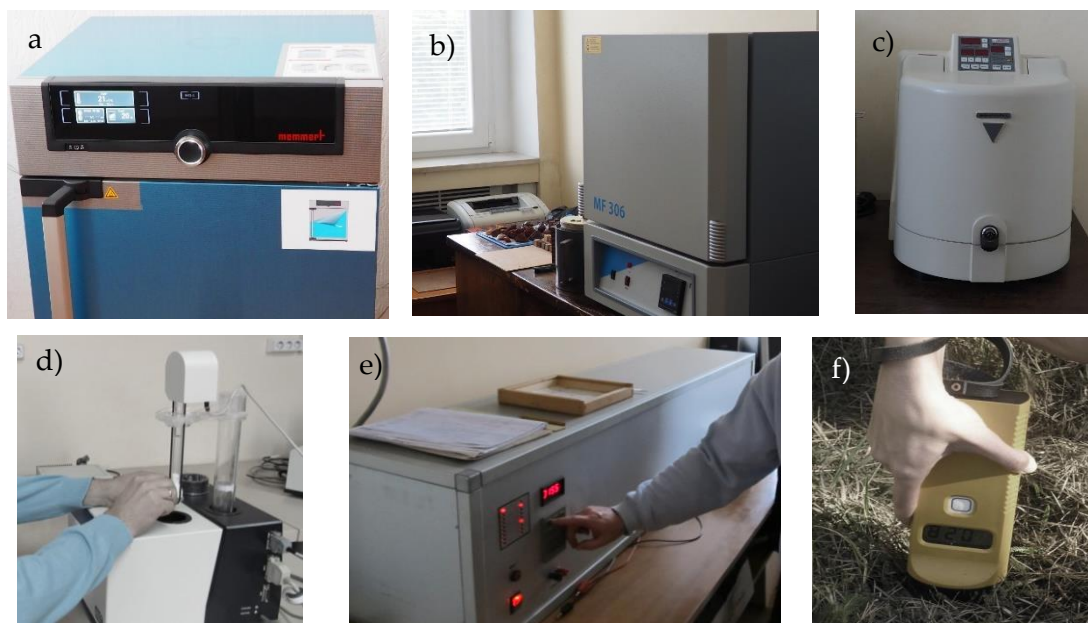


Figure 4. Equipment of the Paleomagnetic laboratory: a) laboratory drying machine for soil and sediment samples; b) muffle furnace used for determination of ancient firing temperatures of archaeological ceramics; c) laboratory grinding machine; d) kappa-bridge MFK-1A (AGICO Ltd., Czech Republic) with automatic rotator for measurements of magnetic anisotropy; e) shielded paleomagnetic oven model MMTD (Magnetic Measurements Ltd., UK) for thermal demagnetization and palaeointensity determination; f) field kappa-meter KT-5 for field measurements of magnetic susceptibility.

One of the main research topic of the Paleomagnetic laboratory - soil magnetism, the research group provides: 1) spatial analyses of indicators of major soil-forming processes and applications in soil classification; 2) evaluation of the effect of wildfires on mineral soil and 3) study of soil erosion and re-distribution due to agricultural or natural factors.

Palaeoclimate reconstructions from loess-palaeosol sequences and magnetic evaluation of anthropogenic pollution are another important topics of the laboratory activities. Results from these research are directly connected with disaster prevention and climate change's investigation.

3. BEST PRACTICES CONNECTED TO DISASTER PREVENTION AND MANAGEMENT, AND ENVIRONMENTAL CHANGES

3.1 TC Seismology - Monitoring of the Mirovo Salt Deposit - a way to assess and reduce natural and technological risks

Seismological hazard is a mandatory part of the Bulgarians national and local disaster management plans. Situated on the Balkan Peninsula, at the margin of the colliding Eurasian and African plates, Bulgaria is characterized by a high frequency of seismic events and the need of specialized studies and assessment for design of structures for earthquake resistance.

Operating the national seismological network, we provide invaluable information not only for the monitoring of natural seismicity by itself but for monitoring of specialized hazardous activities such as salt deposit exploitation for example.

The Mirovo salt deposit is located near the town of Provadia. It is situated in a relatively quiet seismic part of Bulgaria. There is no historical evidence of strong earthquakes occurring in this region. In 1900 and 1902, according to macroseismic data, two earthquakes with magnitudes $M_p=4.1$ and $M_p=4.9$ were felt in the area. From 1902 to 1980 no earthquakes of magnitude greater than 4 have occurred (Grigorova *et al.*, 1979).

The Mirovo salt deposit has been in operation since 1956. The salt is extracted by leaching - technology involving deep erosion of the salt (horizons 1000m, 1200m and 1700m) and subsequent pumping of the saline solution to the surface. As a result of the long period of salt extraction, an underground chamber-pillar system has been formed. Caverns filled with salt solution, with a volume of about 200m³, alternate with intermediary pillars with a diameter of ~ 120-150 m. This process disrupts the natural balance of the salt body and its hosting rocks. It is accompanied by subsidence of the salt diapir surface and collapse of the chambers.

Along with the salt body exploitation, there is considerable industrial activity in the area, including several quarries for gravel and limestone. Although the area is considered seismically weakly active, a significant number of earthquakes occur in the region (Dimitrova *et al.*, 2013, Tzankov and Papratilov, 2013) suggesting that some of the seismic events are induced earthquakes. In the years after 1980, the number of registered weak earthquakes in Provadia grew considerably, especially of those earthquakes with magnitudes up to $M_p=4$.

Using the technical capacity of the seismological network, Dimitrova *et al.* (2020) analyzed seismicity and earth structures in the region of Provadia. A significantly large number of earthquakes (60% of all registered events) are localized within the salt deposit and its close vicinity (Fig. 5). The compiled catalog of the earthquakes within the 50 km region from October 2006 to December 2018 consists of 1082 earthquakes.

The epicenters in the region are concentrated in a cluster oriented in SW–NE direction and crossing the salt body and some fault structures in the area. The depth of most earthquakes reaches up to 2 km. The cluster enlarges in its south-western edge forming a perpendicularly oriented structure that is not associated with any known fault (Vangelov *et al.*, 2013).

There is another seismic cluster on the very southwestern edge of the territory, close to the ROIA seismic station. The depth of these events is between 10 and 15 km, and magnitudes vary in the range $2 < M_p < 3$. This cluster is associated with a seismic swarm active in the second half of 2012 and continued around four months (Dimitrova *et al.*, 2020).

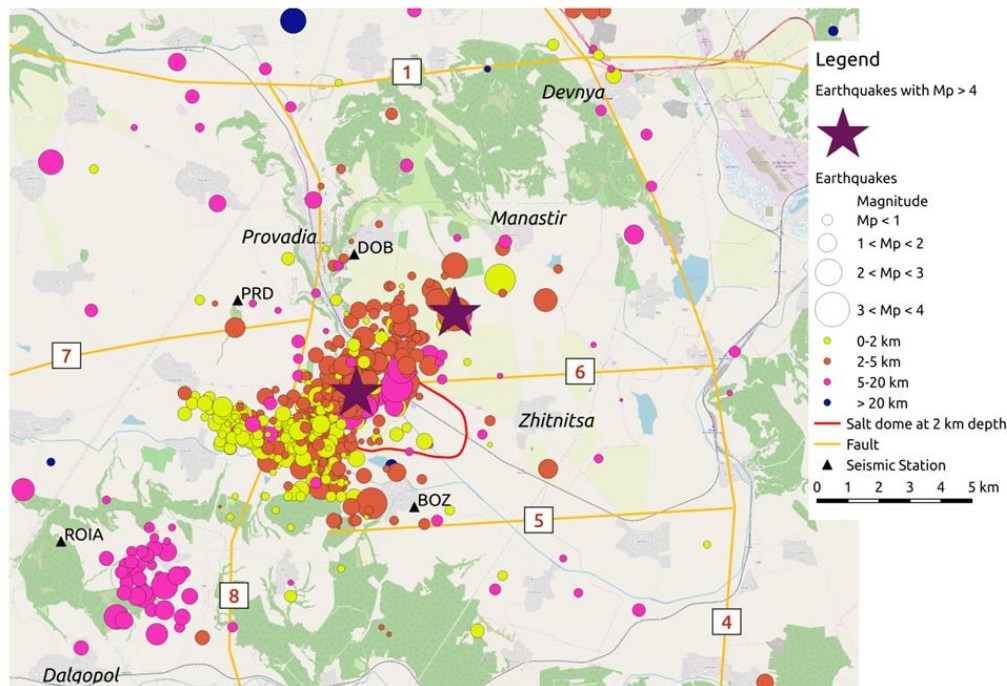


Figure 5. Distribution of seismicity near the Mirovo salt body. The magnitude (M_p) of the earthquakes is marked with circles of different size. Their colors depend on the depth of the events. The main faults in the region are given with yellow lines, and the salt dome is marked with a red curve outlining its shape at the 2 km depth.

The plain solutions of focal mechanisms of the stronger events (Protopopova *et al.*, 2016) does not show a single type – some have normal type faulting, but others exhibit reversed type (some showing insignificant strike-slip component). It can be assumed that the existing fluid transfer changes the stress around the salt body, which might cause trust mechanisms. At the same time, the salt masses with injected fluids might increase the pressure inside the earth's crust, which can lead to normal faulting beneath the body. This fact supports the hypothesis that progression of the mining process disturbs the natural stress field and the fault structures (even those that are fossilized) might be seismically (re)activated.

With the continuous monitoring of the seismicity in the area of the salt deposit, the observed effects can be confirmed and serve as an indicator of upcoming stronger events, which in turn would influence the risk mitigation measures that the local government, the industry and the public must comply to prevent disaster and to ensure the sustainable development of the region.

To increase the accuracy of the hypocentral estimates of events near the salt body, the double difference method, redetermining the hypocentral estimates of 227 events with the HypoDD program is applied. A weak migration of the epicenters towards the salt body is observed, which shows that these events are definitely associated with the exploitation of the deposit and that the accuracy of the hypocentral estimates is high due to the appropriate local network configuration and the proper seismic monitoring.

3.2 Business TC GNSS Data and Data Products - geodetic deformation monitoring in the area of Mirovo salt deposit

The same area is also interesting for geodetic deformation monitoring. The most accurate and modern method for permanent tracking of movements using GPS technology has been applied. The main advantage of the permanent GPS station technology stems from 1) the continuous observation on the change of the station's position in space, and 2) highly accurate quantitative data for displacements within mm.

For monitoring of movements in the area, a permanent GPS station was installed on the territory of the existing seismic station (Provadia, PRD), located 3-4 km away from the salt body. A special observation post with a forced centering device was constructed on the roof of the PRD station where the GPS antenna receiving the signals from the Global Navigation Satellite Systems (GNSS) NAVSTAR and GLONASS was fixed. The position of the antenna was providing visibility of 1° above the horizon to the GNSS satellites (Fig. 2). The observation results are presented with time series of the PARA station coordinates obtained with the GAMIT / GLOBK software (Paskaleva *et al.*, 2010).

During the 3-year monitoring period, the PARA station itself shows a rate of 2 ± 0.5 mm/year in the southwest direction and significant subsidence with a rate of -7.9 ± 1.6 mm/year. Permanent stations VARN, DOBR and AITO (Fig. 6), separated at a distance of 50 km respectively in the east, north-east and south directions have velocities on the order of 1 mm/yr in directions away from the salt deposit. This testifies for the absence of regional movements that would accumulate tectonic stresses in the area.

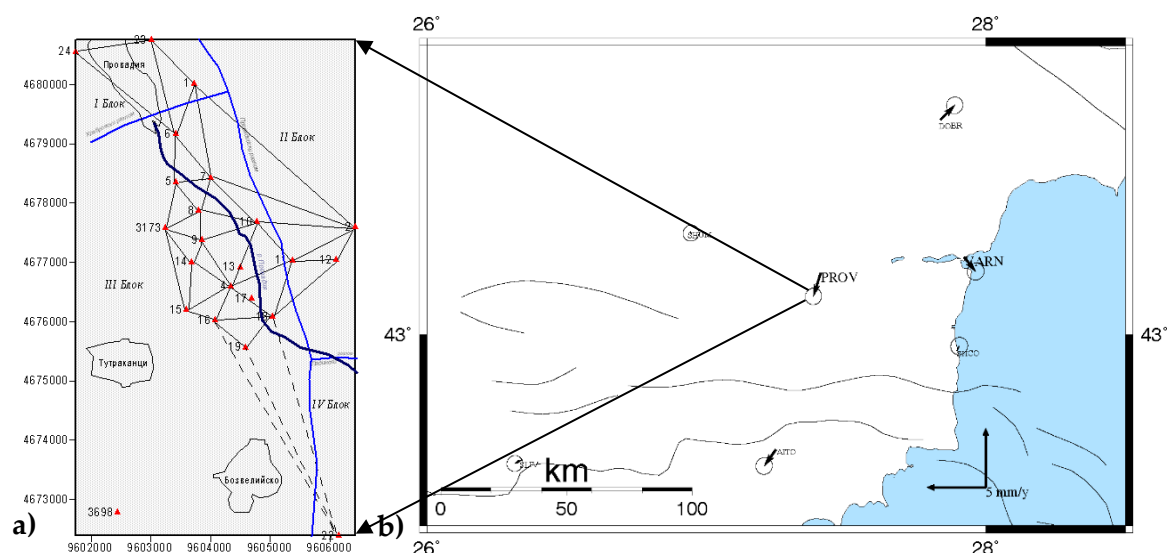


Figure 6. a) Detailed geodetic monitoring network in the area of the salt deposit, remeasured every year with high-precision geodetic methods (Geoprecise Ltd.) and b) Relative to stable Eurasia'2005 velocities (black arrows) from the time series of ETRS89 coordinates of permanent GPS stations in the area within a radius of 50 km around the Mirovo salt deposit.

In order to assess the natural and technogenic risks in the area of the Mirovo salt deposit, data from detailed geodetic monitoring has also been analyzed. That geodetic network was established 30 years ago and was used for annual precision measurements. The control points (Fig. 6) are stabilized with concrete posts equipped with forced centering devices. Lengths between 18 points were re-measured using a laser range finder ME 5000 of the Mekometer company, providing accuracy of the measured distances of the order of (0.2mm + 0.2ppm) and with periodic GPS measurements.

Comparison of the measured lengths shows the relative movement between grid points. The trend of shortening the distances between the points that are located near/and above the salt body is clearly outlined. For example, points 4 and 11 have approached each other in one year by 94.1 mm, 4 and 10 by 83.4 mm, 11 and 18 by 49.7 mm (Fig. 6b). These results allow to conclude that significant local deformations of the earth's surface are taking place in the area of/above the exploitation of the salt deposit, which can explain the induced weak regional seismicity. These local deformation processes probably also affect the permanent GPS station PARA, located 3-4 km from the salt deposit.

The above findings allow us to conclude that there needs to have more regional movements to accumulate considerable tectonic tensions in the study area. On the other hand, the significant local deformations of the Earth's surface that occurred in the area of the exploitation of the salt body may explain the higher level of local seismicity.

3.3 TC Geomagnetic Observation – a regional model of declination for the 2020.0 epoch

The geomagnetic field changes rapidly as a result of solar influence, but at the same time, it also changes slowly under the geodynamo forces. In recent years, scientists have also been looking for a correlation between these processes and climate change (Kitaba *et al.*, 2017). While global observations are needed to study these phenomena, regional high-precision measurements are necessary for practical purposes, such as military topographical applications for example. Carrying out such measurements is a labor-intensive and time-consuming task. Therefore time-space models are often used, which describe with sufficient accuracy the changes in the magnetic field elements (De Santis *et al.*, 2003, Qamili *et al.*, 2010, Kovacs *et al.*, 2015).

To perform successful modelling, scientists need quality data and mathematical techniques. Bulgaria has traditions and infrastructure for geomagnetic observations dating back to the beginning of the XXth century. As a part of NGIC here operates the only one in Bulgaria Geomagnetic observatory in Panagjurishte - PAG (24.177°E, 42.515°N), located in the middle of the country. It was established in 1937 – the first one on the Balkan Peninsula and for 85 years, already performs measurements of the geomagnetic field vector and continuous registration of its variations (Buchvarov, 2020).

Besides the magnetic observatory, the existence of repeat station network is also very important for monitoring the magnetic changes in space and time. It consists of permanently marked sites where accurate measurements of the Earth's magnetic field vector are performed, and this should be done every few years (Dominici and Meloni, 2017). The establishment of the repeat stations network in Bulgaria started in 1934 with eight points which were checked, stabilized, and provided with permanent marks. Now it consists of 27 points uniformly distributed over the entire territory (Metodieiev, 2014).

Using all available data, Metodieiev and Trifonova (2017) generated the latest analytic model called BulGRF of the geomagnetic field over the Bulgarian territory. Results were obtained for the horizontal component, vertical component, magnetic declination, and total intensity values. The field pattern of the horizontal component (H) shows a west-east orientation of the The increase has an amplitude of 800 nT in the southern direction. The magnetic declination (D) isolines have north-northwest orientation varying between 275 and 325 arcmins. The gradient of the vertical component Z has a north-northeast direction and an amplitude of 2000 nT. The total F field intensity combines the H and Z variation, resulting in a well-defined northwest–southeast trend ranging from 47,100 to 48,100 nT.

Here, the updated model for 2020.0 epoch is presented based on the new data from PAG , SUA, GCK and PEG observatories and all repeat stations from Bulgarian network (Metodieiev and Trifonova, 2020). Accordingly, it has been updated, and local anomalies of smaller wavelengths were added.

For the 2020.0 model elaboration, the correlation between the secular variation trends in PAG observatory and secular variation trends of each component in all repeat stations for the same period was investigated. Thus, coefficients were obtained, allowing calculation of the secular variations of the geomagnetic field elements in each repeat station for long intervals without real measurements.

The magnetic declination is the most used element of the magnetic field for practical purposes, widely utilized in geodesy, cartography, and their associated navigational systems. It is incorporated in the naval navigation maps and is used in the navigation process. It is also a significant factor for aviation where declination data are important for every airport (civil or military).

The average value of the declination in Bulgaria has been increasing steadily over the last 20 years, starting from below 200 min. in the year 2000 and reaching over 300 min. at present. A stable southwest-northeast trend is observed in all models, as a base on which local anomalies are superimposed. Values of the 2020.0 declination model over the Bulgarian territory range between 218 and 422 min (Fig. 7). In dark colors, anomalous regions connected with ore deposits rich in magnetic minerals are outlined, as for example, those near the towns Haskovo, Yambol, and Burgas. The large polymetallic bodies near the PAG observatory are also delineated.

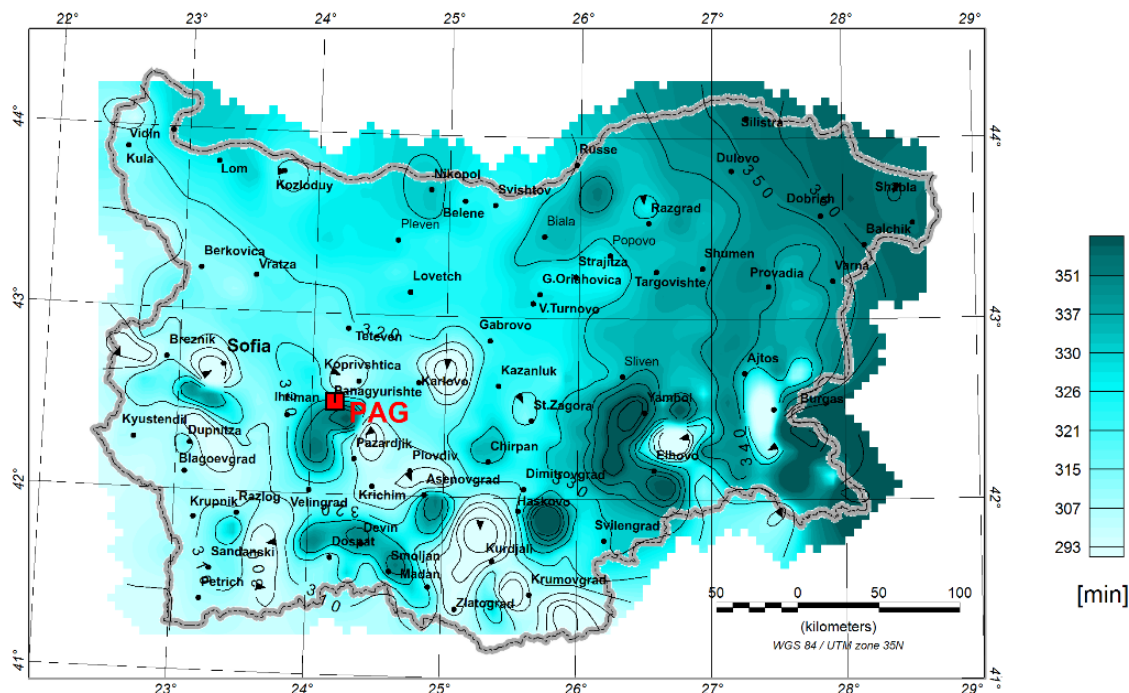


Figure 7. Map of the spatial distribution of declination D [min] for the 2020.0 epoch (modified from Metodiev and Trifonova, 2020). Values range between 218 min. (bright colors) and 422 min. (dark colors).

Since the forces that generate our magnetic field are constantly changing, the field itself is also in continual flux, its strength and orientation are fluctuating over time. This causes the variation of Earth's magnetic field and determines the benefit of up-to-date models for those using some kind of a compass.

3.4 TC Multi-Scale Laboratories – variations of magnetic characteristics as sensitive indicators for soil evolution in response to environmental changes

Healthy and sustainable soil is an essential prerequisite for successful fight against poverty and hunger of the Earth's population. That is why studies focused on the evolution of soil properties in response to changes in environmental conditions can give important information on future changes caused by global warming. Iron oxides are among the most sensitive soil mineral constituents against changing redox environment, temperature, and water balance (Cornell and Schwertmann, 2003). Strongly magnetic iron oxides are formed “in situ” in the soil column during chemical transformations under surface weathering conditions (Schaetzl and Anderson, 2009). Depth variations of different magnetic parameters along soil profiles have been proven as effective indicators for the intensity and variability of soil forming processes (Jordanova, 2016).

In the following example, we show how magnetic studies of a Holocene soil can provide precise information on the effects of environmental changes during the Holocene era on soil

properties. The soil profile was sampled near the village of Kolobar (Silistra district) (43.7833°N, 27.1833° E). According to the national soil map of Bulgaria, soil cover in this area is represented by strongly leached Chernozem. The total thickness of the upper humic, transitional and illuvial horizons comprise 90 cm with clearly marked color changes. Parent material is represented by loess sediments deposited during the last glacial period (Evlogiev, 2007). The present day long term mean annual temperature (MAT) is 12.8°C, and mean annual precipitation is 510 mm.

The cleaned outcrop was sampled down to 160cm depth continuously at each 2cm interval, resulting in 80 samples in total. Bulk powder material of about 300g weight from each depth level was gathered. Magnetic measurements of susceptibility and its frequency dependence were carried out on powder samples, while magnetic remanences were imparted to laboratory prepared solid cubic (2x2x2cm) samples.

Equipment of the Paleomagnetic laboratory at NIGGG, included in EPOS-TCL infrastructure includes up-to-date instruments allowing detailed analyses of the magnetic signal of natural materials. Magnetic susceptibility was measured on MFK-1A kappabridge (AGICO, Czech Republic) at two frequencies – low (976 Hz) and high (15616 Hz) - in a 200 A/m magnetic field. Frequency-dependent magnetic susceptibility $\chi_{fd} = (\chi_{lf} - \chi_{hf})$ was calculated. Anhysteretic remanent magnetizations (ARM) were imparted using a Molspin AF demagnetizer. AF peak amplitude was 100 mT superimposed on a 50 μ T static dc field along the samples z-axis. Isothermal remanent magnetization in a 2T dc field was imparted using an ASC IM-10-30 pulse magnetizer (ASC Scientific, USA). After IRM acquisition, samples were placed in a mu-metal shielded boxes and kept for seven days. Viscous remanence (VRM) was estimated by the difference in the signal between initial and after zero field cleaning (ZFC) IRM intensity. Remanences were measured using a JR-6A automatic spinner magnetometer (AGICO Ltd., Czech Rep.) with a sensitivity of 2×10^{-6} A/m.

Significant results from this case study are presented in Fig. 8. Depth variations of magnetic susceptibility (χ) (Fig. 8 a) give first information on the relative importance of pedogenic magnetic enhancement concerning the magnetic signal of the parent loess. Before the sharp increase at 86 cm depth, magnetic susceptibility continuously evolves towards higher values, signifying increased production of pedogenic strongly magnetic phases with climate amelioration at the Holocene / Last glacial maximum boundary. Better insight on the grain size changes of the pedogenic strongly magnetic fraction is gained from the variability of the grain size sensitive magnetic parameters.

Frequency dependent susceptibility (χ_{fd}) (Fig. 8 b) shows maxima when magnetic assemblage is dominated by superparamagnetic (SP) magnetite / maghemite (typically in the size range of 10 – 15 nm). Viscous remanence VRM (Fig. 8c) is carried preferentially by thermally instable single domain (SD) particles with diameters close to the critical SP – SD threshold (Dunlop and Ozdemir, 1997). With further increase in effective magnetic grain size, particles exist in a stable SD state and most effectively acquire an ARM magnetization (Maher,

1988). As seen from Fig. 8 b, c, d), maxima on the three curves along the profile occur at different depths.

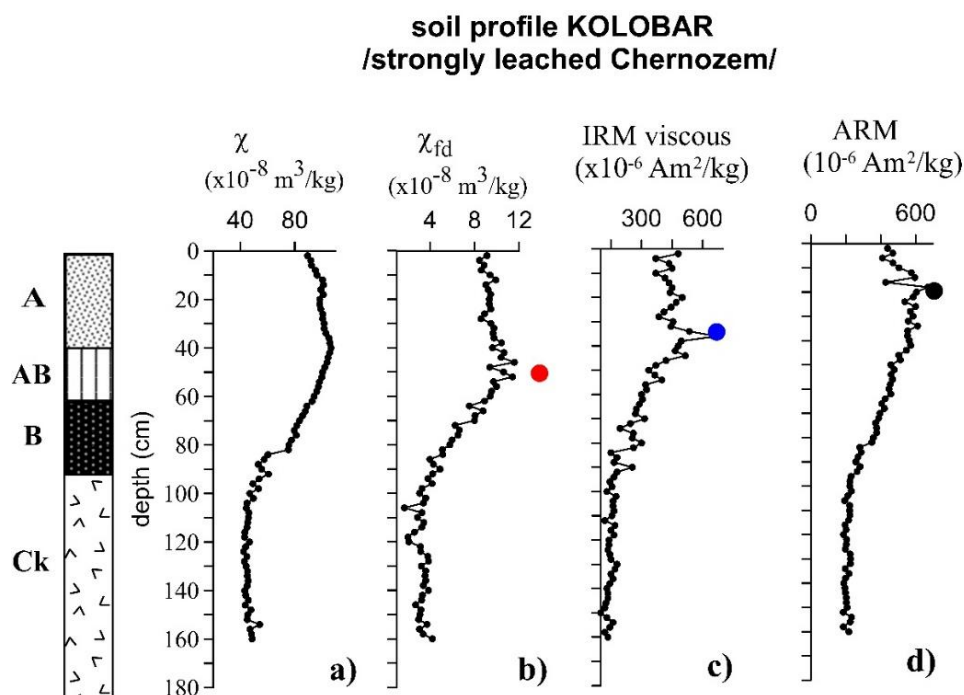


Figure 8. Variations of magnetic parameters with depth of the Holocene soil at Kolobar: a) mass specific magnetic susceptibility (χ); b) frequency-dependent magnetic susceptibility (χ_{fd}); c) viscous Isothermal remanent magnetization (IRM viscous); d) Anhyseretic remanent magnetization (ARM). Color dots indicate depths of the corresponding maximum value of the parameter along the soil thickness. The soil column is shown on the left: A – humic horizon, AB – transitional A-B horizon; B – illuvial horizon, Ck – parent loess material with carbonates.

The highest concentration of the smallest SP fraction occurs at 46 (52) cm depth, while larger viscous particles are most enriched at 36 cm depth (Fig. 8 b, c). The largest pedogenic magnetic grains existing in the SD domain state show a maximum at the shallowest depth (18 cm). This well-expressed separation among the positions of the maximum enhancements of different magnetic grain size fractions can be related to the type and nature of pedogenic processes acting during the soil formation. The concept behind this hypothesis is presented in detail in Jordanova and Jordanova (2020). Briefly, such consecutive increase in depths of the maxima in grain size sensitive magnetic proxy parameters from coarsest to finest magnetic fractions indicates that soil formation occurs without dust additions. This is a significant result, contributing to the knowledge on the global dust dynamics (Muhs, 2013). Moreover, soil formation mechanism strongly depends on the presence or absence of contemporaneous dust sedimentation, changing depth distributions of various soil constituents (Lowe and Tonkin, 2010; Eger *et al.*, 2012). Thus, solving the problem of identification of dust additions during pedogenesis by magnetic

measurements is another valuable contribution of geophysics to the studies of Earth's environment.

4. DISCUSSION AND CONCLUSIONS

The National Geoinformation Center (NGIC) unites scientific infrastructures and their associated data and services with scientific research and expertise into one integrated system. Figure 9 shows the locations in Bulgaria of the various stations in the NGIC and an example of neighboring geomagnetic observatories and GNSS stations which are part of the EPOS. Providing this information to EPOS data portal allows scientists to benefit from adding data from adjacent countries. EPOS relies on the National Research Infrastructures (NRIs) as NGIC, which represent the actual data providers of quality-checked data and products. NRIs contributing to EPOS are owned and managed at a national level which has a significant economic value both, in terms of construction and yearly operational costs. The federated system of Thematic Core Services is the skeleton of the EPOS delivery framework and represents the solution for integrating national infrastructures. Thus, the federated system gives researchers invaluable opportunities to use and analyze multidisciplinary solid Earth science data.

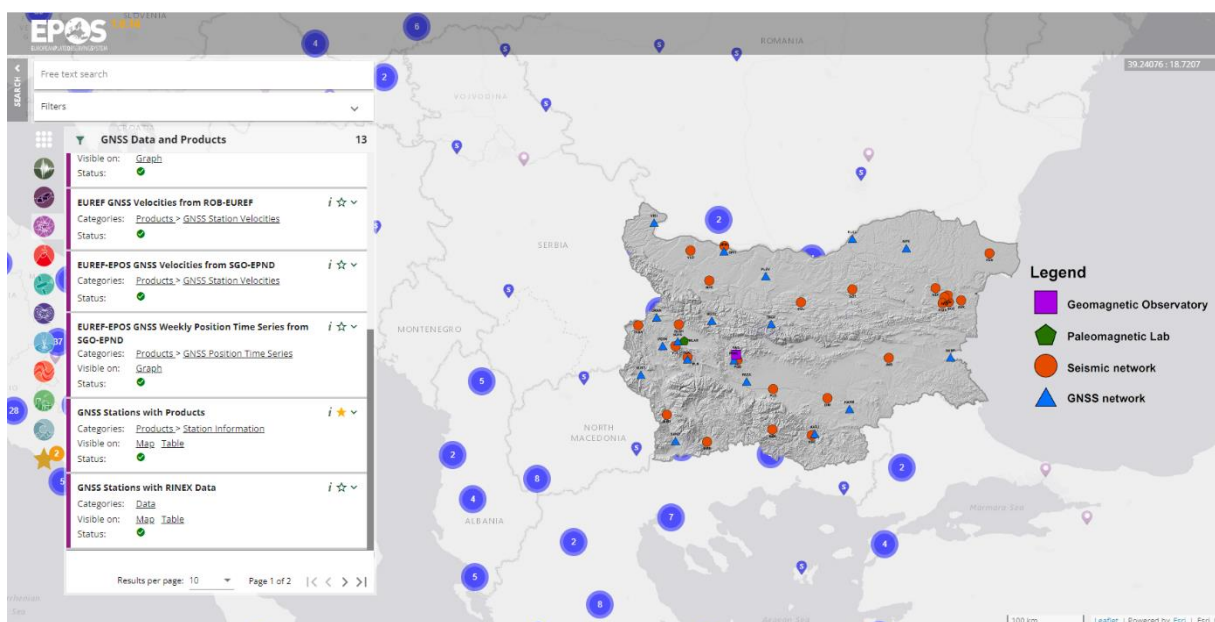


Figure 9. Map of the locations of the different stations in Bulgaria with symbols described in the legend. In the background is given a map from the EPOS Data Portal showing an example of neighboring geomagnetic observatories (pink circles) and GNSS stations (blue circles)

<https://www.ics-c.epos-eu.org/>

By improving and facilitating the integration, access, use, and re-use of Earth science data, data products, services and facilities, NGIC is developing a holistic, sustainable, multidisciplinary research platform to provide quality controlled data from diverse Earth science disciplines. At the same time following the model of EPOS, NGIC is designed to foster scientific and technological innovation for successfully addressing global challenges in our planet.

The scientific results presented in this paper cover different topics like seismologic and geodetic analysis, magnetic field modelling and laboratory experiments. Beyond the specific scientific value that has been achieved by the application of each of the described methods and case studies, the possibilities of conducting research in different thematic areas using the technical capacity of a scientific infrastructure uniting all directions in the Earth Sciences is demonstrated. The interpretation of seismological and geodetic data in the region of the Mirovo salt deposit convincingly shows the presence of induced seismicity, as well as crustal deformations related to salt extraction processes. The presented up-to-date geomagnetic model for the territory of Bulgaria provides data for regional mapping, and for reducing exploratory magnetic surveys in this area. Laboratory magnetic measurements of 160 cm deep soil profile reveal precise information on the effects of environmental changes during the Holocene era on soil properties and shows the advantages of using new magnetic parameter for tracking the presence or absence of dust additions during soil forming period.

Open access to quality controlled data and scientific products is an essential step forward to unraveling and interpreting geo-processes with the final goal of forecasting their impact on the environment and society. Natural phenomena such as earthquakes and extreme weather impact society by damaging the economy, security and harming the safety of the environment and the planet's population. Consequently, combining many diverse disciplines such as geology, seismology, geodesy, and geomagnetism is the domain where the Earth system and its phenomena can be unraveled and better understood.

With the inclusion in the EPOS thematic packages and the provision of real-time data to their integrated core services, NGIC supports pan-European integration of research infrastructures to advance the ability to respond to fundamental scientific and socio-economic questions related to geo-hazards and georesources.

Last but not least, the activities of NGIC include also oceanographic and bio-chemical monitoring of the Black Sea. It provides sea level data, maps of the horizontal distribution of seawater temperature and salinity, distribution maps of the main categories of macro waste on the sea surface, data on phytoplankton bloom concentrations species, abundance and biomass data of invasive zooplankton species and so on. Although outside the scope of the EPOS thematic areas, we envisage including this information and data as part of the products provided by the NGIC infrastructure.

Further development of the NGIC infrastructure activities includes landslides and near-fault observations, as well as monitoring of the concentration of radon activity (Rn-222). Ten

RD200M radon registration sensors and the necessary electronics were purchased. They are installed in appropriate stations of the seismological network on the territory of the country and inside three caves. As is known, the increase in the concentration of radon gas is associated with tectonic processes related to earthquakes. Except for purely scientific purposes, measurements of radon should be considered in preparing the national action plan to address long-term risks from radon exposures, according to the implementation of the European Council Directive No. 2013/59/EURATOM.

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REFERENCES

- Atanasova M., Nikolov H., (2016). Detection of the Earth's crust deformation in Provadia area using InSAR technique. Proceedings of XXVI International symposium on “Modern technologies, education and professional practice in geodesy and related fields”, 2016, 1-12.
- Buchvarov, I. and Kostov, K. (1981). Presentation of the geomagnetic field in Bulgaria for 1960.0, 1965.0 and 1970.0 with second degree polynomial of geographical coordinates, *Bulg. Geophys. J.*, 7 (1): 51–62 (*in Russian*).
- Buchvarov, I. and Cholakov, I. (1994). Geomagnetic field of the territory of Bulgaria – 1990.0, *Bulg. Geophys. J.*, 20 (4): 58–65 (*in Bulgarian*).
- Buchvarov, I. (2020). Geomagnetic field, geomagnetic measurements and models, field mapping. *Bulgarian Geophysical Journal*, 43 (1): 98-109. <https://doi.org/10.34975/BGJ-2020.43.9> (*in Bulgarian*).
- Constantin, D., Mason, J.A., Veres, D., Hambach, U., Panaiotu, C., Zeeden, C., Zhou, L., Marković, S.B., Gerasimenko, N., Avram, A., Tecsă, V., Groza-Sacăciu, S.M., del Valle Villalonga, L., Begy, R., Timar-Gabor, A. (2021). OSL-dating of the Pleistocene-Holocene climatic transition in loess from China, Europe and North America, and evidence for accretionary pedogenesis. *Earth Sci. Rev.*, 221, Article 103769 <https://doi.org/10.1016/j.earscirev.2021.103769>
- Cornell, R., Schwertmann, U. (2003). *The Iron Oxides. Structure, Properties, Reactions, Occurrence and Uses*. Weinheim, New York.
- De Santis, A., Gaya-Pique, L. R., Dominici, G., Meloni, A., Torta, J. M., and Tozzi, R.(2003). Italian Geomagnetic Reference Field (ITGRF): update for 2000 and secular variation model up to 2005 by autoregressive forecasting, *Ann. Geophys.*, 46: 491–500.
- Dimitrova L., Solakov D., Simeonova S., Aleksandrova I., and Georgieva G. (2015). Analysis of the seismicity in the region of Mirovo salt mine after 8 years monitoring. EGU April

- 2015, Vienna, Austria, <https://meetingorganizer.copernicus.org/EGU2015/EGU2015-11419.pdf>
- Dimitrova, L., Georgieva, G., Trifonova, P., Oinakov, E., Protopopova, V., Metodiev M. (2020). Seismic sources and Earth structure in the transition zone between Fore-Balkan unit and Moesian platform, NE Bulgaria. *Acta Geod Geophys* 55: 183–202. <https://doi.org/10.1007/s40328-020-00288-3>
- Dominici G, Meloni A. (2017) The Italian magnetic repeat station network: results from the 2012.5 ‘Reduced Network’ completion. *Ann. Geophys.* 60(2). <https://doi.org/10.4401/ag-7062>
- Dunlop, D., Özdemir, O. (1997). *Rock Magnetism. Fundamentals and Frontiers*. In: Edwards, D. (Ed.), *Cambridge Studies in Magnetism*. Cambridge University Press.
- Eger, A., Almond, P.C., Condrón, L.M. (2012). Upbuilding pedogenesis under active loess deposition in a super-humid, temperate climate — quantification of de-position rates, soil chemistry and pedogenic thresholds. *Geoderma*, 189–190: 491–501, <https://doi.org/10.1016/j.geoderma.2012.06.019>.
- Evlogiev, Y. (2007). Evidence for the aeolian origin of loess in the Danubian plain. *Geol. Balk.* 36 (3-4), 31-39. <https://doi.org/10.52321/geolbalk.36.3-4.31>
- Finlay, C. C., Olsen, N., Kotsiaros, S., Gillet, N., and Tøffner-Clausen, L. (2016). Recent geomagnetic secular variation from Swarm and ground observatories as estimated in the CHAOS-6 geomagnetic field model, *Earth Planet. Space*, 68: 1–18, <https://doi.org/10.1186/s40623-016-0486-1>.
- Grigorova E., D. Sokerova, L. Christoskov and Sn. Rizjikova (1979). Catalogue of the earthquakes in the territory of Bulgaria for the period 1900-1977, Archives of the Geophysical Institute of BAS, Sofia.
- Haines, G. V. (1990). Regional magnetic field modeling: a review, *J. Geomagn. Geoelectr.*, 42: 1001–1018. <https://doi.org/10.5636/jgg.42.1001>
- Kenyeres, A., Bellet, J.G., Bruyninx, C. *et al.* (2019). Regional integration of long-term national dense GNSS network solutions. *GPS Solut* 23, 122. <https://doi.org/10.1007/s10291-019-0902-7>
- Kitaba, I., Hyodo, M., Nakagawa, T. *et al.* (2017). Geological support for the Umbrella Effect as a link between geomagnetic field and climate. *Scientific Reports* 7, 40682. <https://doi.org/10.1038/srep40682>
- Kostov, K., Cholakov, I. and Buchvarov, I. (1991). The geomagnetic field on the territory of Bulgaria – epoch 1980.0, *Bulgarian Geophys. Journal*, 17, 42-54.
- Kovács, P., Vujić, E., Csontos, A., Brkić, M., and Vadász, G. (2015). Comparison of regional field models compiled by different methods for the area of Croatia and Hungary, in: *Abstr. 7th MagNetE Workshop* 16–18 September, Budapest, Hungary.
- Jordanova, N. (2016). *Soil Magnetism. Applications in Pedology, Environmental Science and Agriculture*. 1st Edition, Academic Press (Elsevier), 2016, ISBN: 9780128092392, pp. 1–446.
- Jordanova, D., Jordanova, N. (2020). Diversity and peculiarities of soil formation in eolian landscapes – Insights from the mineral magnetic records. *Earth and Planetary Science Letters*, 531, 115956. <https://doi.org/10.1016/j.epsl.2019.115956>

- Lowe, D.J., Tonkin, P.J. (2010). Unravelling upbuilding pedogenesis in tephra and loess sequences in New Zealand using tephrochronology. In: Gilkes, R.J., Prakongkep, N. (Eds.), *Proceedings of the 19th World Congress of Soil Science; Soil Solutions for a Changing World*, Brisbane, pp.34–37.
- Maher, B.A. (1988). Magnetic properties of some synthetic sub-micron magnetites. *Geophys. Journal*, 94: 83–96.
- Metodiev, M. and Trifonova, P. (2017). Bulgarian Geomagnetic Reference Field (BulGRF) for 2015.0 and secular variation prediction model up to 2020, *Annales Geophysicae*, 35(5): 1085-1092, <https://doi.org/10.5194/angeo-35-1085-2017>
- Metodiev, M. (2014). Modelling of declination's secular variation for the purposes of regional topographic mapping. *Bulgarian Geophysical Journal*, 40(1): 76-84. <https://doi.org/10.34975/BGJ-2014.40.7>
- Muhs, D.R., (2013). The geologic records of dust in the Quaternary. *Aeolian Research*, 9, 3 – 48.
- Paskaleva I., Nikolova S., Dimitrova L., Georgieva G. (2010). Monitoring networks - way for improving risk assessment from natural and man-made hazards: case study salt mine Provadia (NE Bulgaria) *Acta Geodaetica et Geophysica Hungarica*, 45(3): 388-402. <https://doi.org/10.1556/AGeod.45.2010.3.11>
- Protopopova V, Georgiev I, Botev E, Dimitrov D (2016). Geodynamics on Northern Bulgarian seismic zones. In: Proceedings of 8th BGGS national conference, 25 November 2016, Sofia, Bulgaria (*in Bulgarian*)
- Qamili, E., De Santis, A., Cianchini, G., Duka, B., Gaya-Piqu, L. R., G. Dominici, G., and Niko Hyka, N. (2010). Two geomagnetic regional models for Albania and south-east Italy from 1990 to 2010 with prediction to 2012 and comparison with IGRF-11, *Earth Planet. Space*, 62: 1–9. <https://doi.org/10.5047/eps.2010.07.011>
- Rousseau D.-D., Svensson, A., Bigler, M., Sima A., Steffensen, J.P., Boers N., (2017). Eurasian contribution to the last glacial dust cycle: how are loess sequences built? *Clim. Past*, 13, 1181–1197. <https://doi.org/10.5194/cp-2017-67>
- Schaetzl, R., Anderson, A. (2009). *Soils. Genesis and Geomorphology*. Cambridge Univ. Press, UK. ISBN978-0-521-81201-6.
- Shanov, S. (2005). Post-Cretaceous to recent stress fields in the SE Moesian Platform (Bulgaria), *Tectonophysics*, 410 (1-4): 217-233 <https://doi.org/10.1016/j.tecto.2005.06.009>
- Solakov D. (1993). An algorithm for determining the main kinematic parameters of nearby earthquakes, *Bulg. Geophys. Journ.* 19 (1): 56-69. (in Bulgarian)
- Solakov D., Simeonova S., Trifonova P., Georgiev I., Raykova P., Metodiev M., Aleksandrova I. (2019). *Building Seismic Risk Management, Part 2: Probabilistic Seismic Hazard Assessment* BAS Publ. House, S., ISBN 978-954-322-988-8, pp. 13-110 (in Bulgarian).
- Thébault, E., Finlay, C., Beggan, C., *et al.* (2015). International Geomagnetic Reference Field 12th Generation (IGRF-12), *Earth, Planet. Space*, 67: 1–19. <https://doi.org/10.1186/s40623-015-0228-9>
- Tsankov, H. and Papratilov, I. (2013). A program to solve the reverse gravimetric task by optimizing patterns comprised of a finite number of three-dimensional prismatic bodies. *Annual of University of mining and geology “St. Ivan Rilski” – Sofia*, v. 56, Part I:

Geology and Geophysics, p. 157-162 <https://mgu.bg/wp-content/uploads/2022/02/Vol.-56-I-2013.pdf>

Vangelov D., H. Kiselinov, P. Andreeve, V. Vangelova (2013). Structural characteristics for a part of the Eastern Fore-Balkan. *Review of the BGS*, 74(1-3): 21-39 (in Bulgarian).

Varga, G., (2015). Changing nature of Pleistocene interglacials – is it recorded by paleosoils in Hungary (Central Europe)? *Hungarian Geographical Bulletin*, 64, 4, 317 – 326.