35 YEARS OF RESEARCH ON THE STRUCTURE AND DYNAMICS OF THE SOLID EARTH – A REVIEW

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The paper reviews research conducted by the Solid Earth Dynamics Department in the Institute of Geodynamics "Sabba S. Stefănescu" since the foundation of the organisation.
Description was split into two parts: (i) activities developed during the 20th century by the Geodesy Department, whose successor the Solid Earth Dynamics Department is, and (ii) research performed after the Solid Earth Dynamics Department was created.
Main research directions are systematically presented: seismology, crust deformation, gravity field and its space-time changes, geomagnetic investigations, tectonic setting of geodynamic active areas, numerical models of lithosphere based on the interpretation of gravity and/or geomagnetic data, and numerical simulations of upper mantle dynamics.
Since the beginning, the Solid Earth Dynamics Department has focused attention on the Vrancea seismic zone and conducted various research for unveiling mechanisms of the intermediate-depth earthquake unusually triggered within full intracontinental environment, and no active subduction. Based on EU funds, a High-Performance Computing Cluster has been constructed for numerical modelling of several possible geodynamic scenarios of the Vrancea seismic zone evolution, marking the first milestone in the implementation of numerical geodynamics in Romania.
The paper also presents the department participation at national and/or international projects as well as scientific cooperation with national/international research organisations, and activities aimed at solving industry problems.
Academic awards and prizes got for exceptional scientific achievements close the presentation.

Keywords: geodynamics, geodesy, gravity, geomagnetism, seismology, numerical geodynamics, Vrancea.

1. BEGINNINGS

The Solid Earth Dynamics Department (SEDD) is the successor of the Geodesy Department, created at the founding of the Institute of Geodynamics of the Romanian Academy.

Research on deformations of the crust using geodetic methods began in Romania in 1970s through collaboration between geodetic institutions such as the Military Topographic Directorate (DTM), the Institute of Geodesy, Photogrammetry, Cartography, and Territorial Organization (IGFCOT), and geological institutions like the State Committee for Geology, the Institute of Applied Geophysics, and the National Institute for Earth Physics (NIEP). Investigations consisted of repeated determinations within high-order geodetic networks and levelling polygons across the national territory.

Later, a special team dedicated to geodynamic studies, initially within NIEP, and starting in 1990, within the "Sabba S. Ștefănescu" Institute of Geodynamics of the Romanian Academy (IGSSS), carried out the research.

To address problems related to crust dynamics and associated phenomena, three main geodynamic polygons were designed (Fig.1.1): Crăciunești–Sarmisegetuza–Padeș, Căldărușani–Tulnici, and Mangalia–Sulina.

Although field observations were conducted in all three polygons, the primary focus was on the Căldărușani–Tulnici polygon, which includes the Vrancea seismic zone. After 1991, the polygon was reduced by transforming an older second-order levelling line between Focșani and Sfântu Gheorghe into a first-order line, following the route Focșani–Vidra–Valea Sării–Tulnici–Greșu–Tg. Secuiesc–Covasna–Sf. Gheorghe. First, the line was completely measured through geometric levelling in two successive stages (1990 and 1991), but later, only some active segments in the epicentres area were subject to repeated surveys.

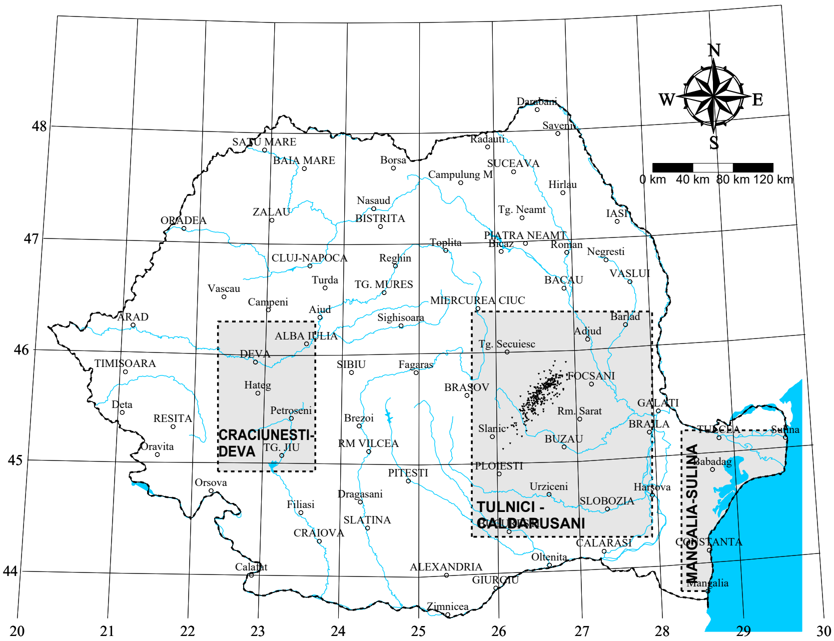

Figure 1.1. The infrastructure for monitoring lithosphere dynamics in Romania: geodynamic polygons.

For more detailed research, several micro-polygons were created within the central polygon (Fig. 1.2): (1) Tulnici, (2) Nereju, and (3) Odobeşti.

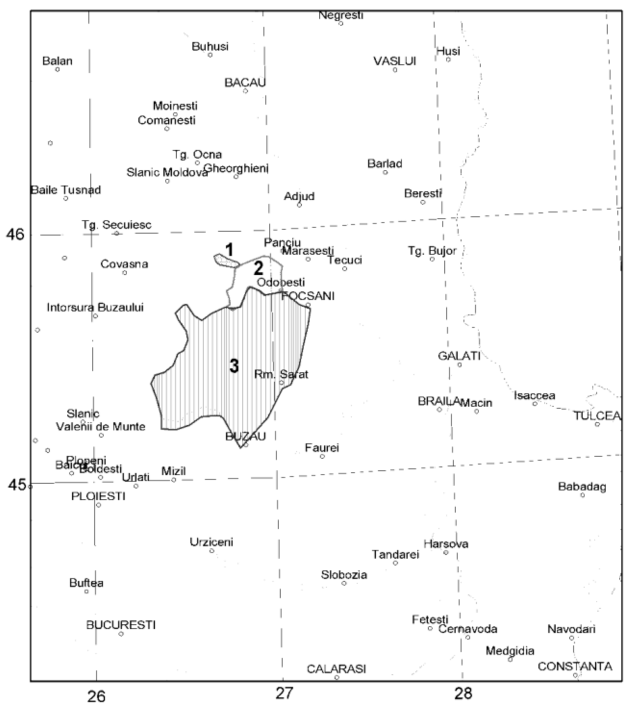

Figure 1.2. Location of geodetic micro-polygons in the East Carpathian Bend Area.

The geodetic studies were conducted almost entirely within micro-polygon No. 1 (Tulnici-Valea Sării-Vrâncioaia), with emphasis on monitoring the faults across it. The micro-polygon is situated in the epicentre area of upper mantle earthquakes in the Vrancea zone and consists of about 100 levelling stations (Fig. 1.3) designed for repeated high-precision determinations to study the vertical deformations of the Earth's crust in active geodynamic areas.

Each station of the polygon consists of a buried levelling benchmark (Fig. 1.4), made by a cemented shallow borehole, with a porcelain ball on top for placing the levelling rod.

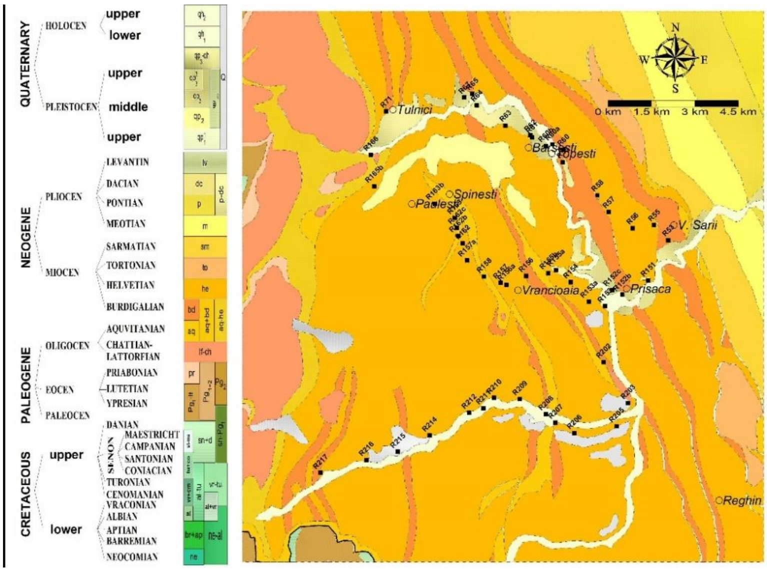

Figure 1.3. Geological framework for the location of the stations of Micro-polygon no. 1.

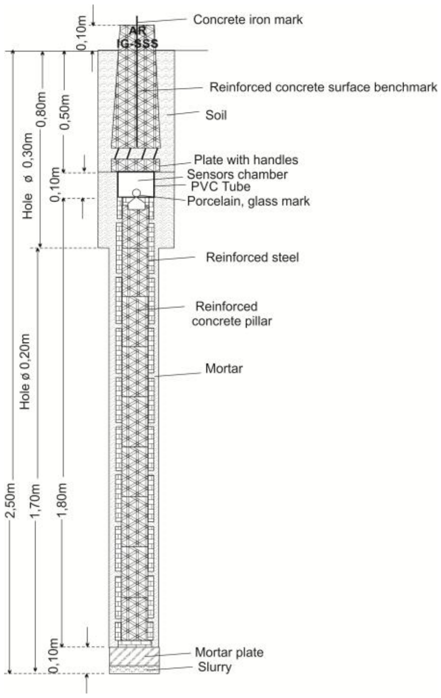

Figure 1.4. Levelling benchmark from Micro-polygon No. 1.

Lörinczi (2000) and Lörinczi and Cadicheanu (2001) developed special mathematical methods to process observations and establish the most probable values of the crust deformations.

The results of observations were subject to several papers (Zugrăvescu *et al*., 1995; Zugrăvescu & Polonic, 1997; Zlăgnean *et al*., 2001; Lörinczi *et al*., 2001; Zugrăvescu *et al*., 2006; Zlăgnean *et al*., 2006), and some of them are presented in Figures 1.5–1.6.

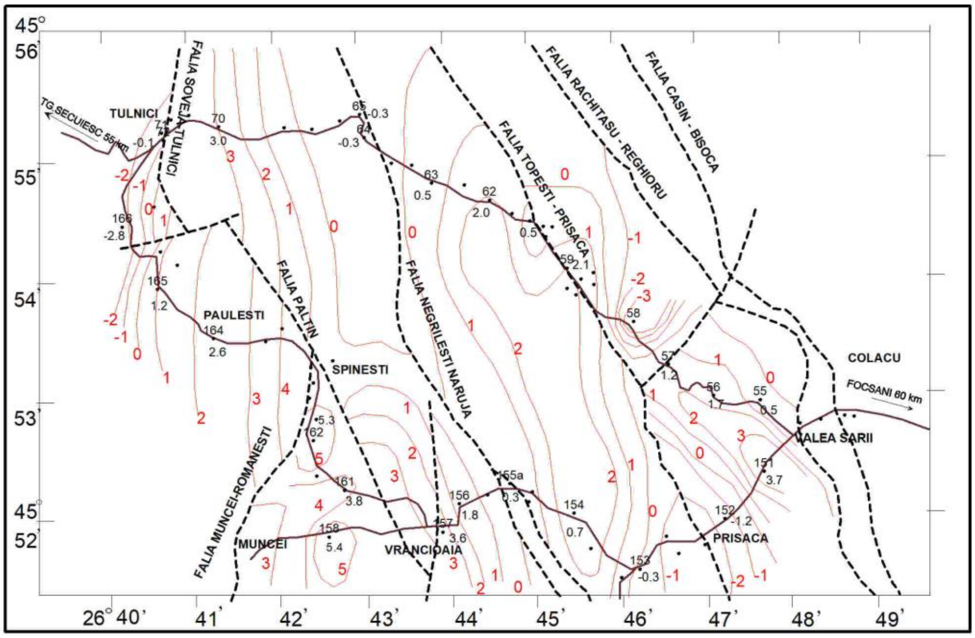

Figure 1.5. Vertical crustal deformations within micro-polygon No. 1 between 1990–1994 (after Zugrăvescu & Polonic, 1997).

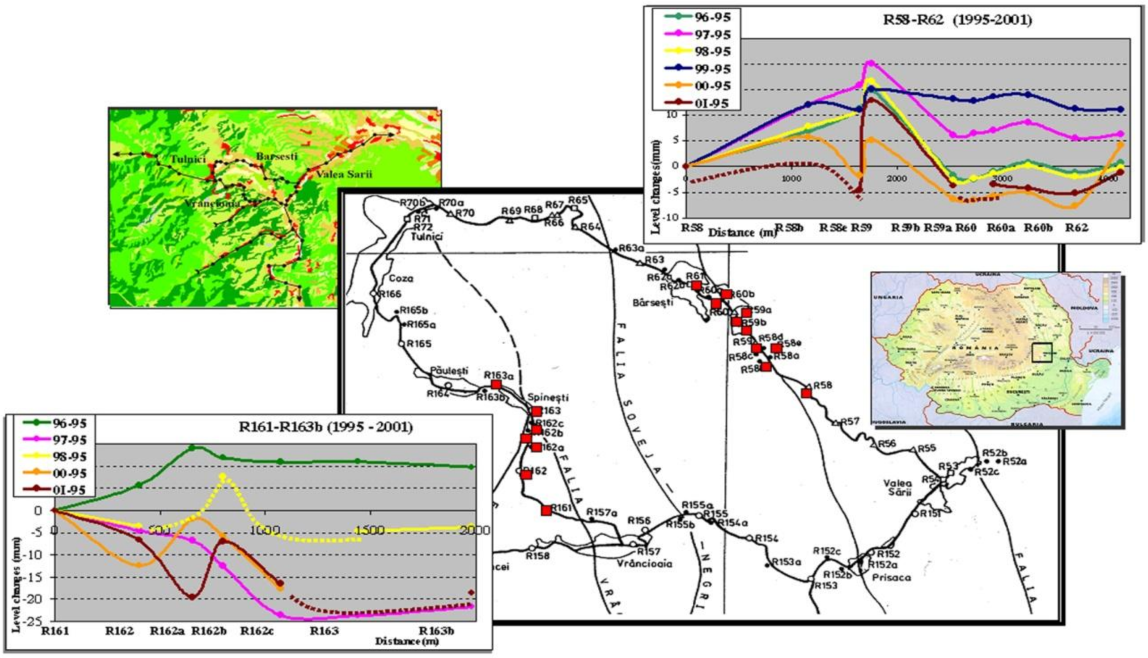

Figure 1.6. Vertical crustal movements recorded within micro-polygon no. 1 between 1995–2001 (after Zlăgnean *et al*., 2001).

Geodesy investigations conducted within the East Carpathian bending area were supplemented by studies addressing the regional stress that triggers larger-scale geodynamic phenomena, such as the extension associated to the formation of the Transylvanian Depression (Polonic, 1996), or the geodynamic processes that generated Banat seismicity (Polonic & Malița, 1997).

Zugrăvescu *et al*. (1998) compiled a map of recent crustal movements on the territory of Romania, by distinctly considering its tectonic compartments (Fig. 1.7), while Polonic (2000) constructed a map of the Neogene vertical movements on the Romanian territory.

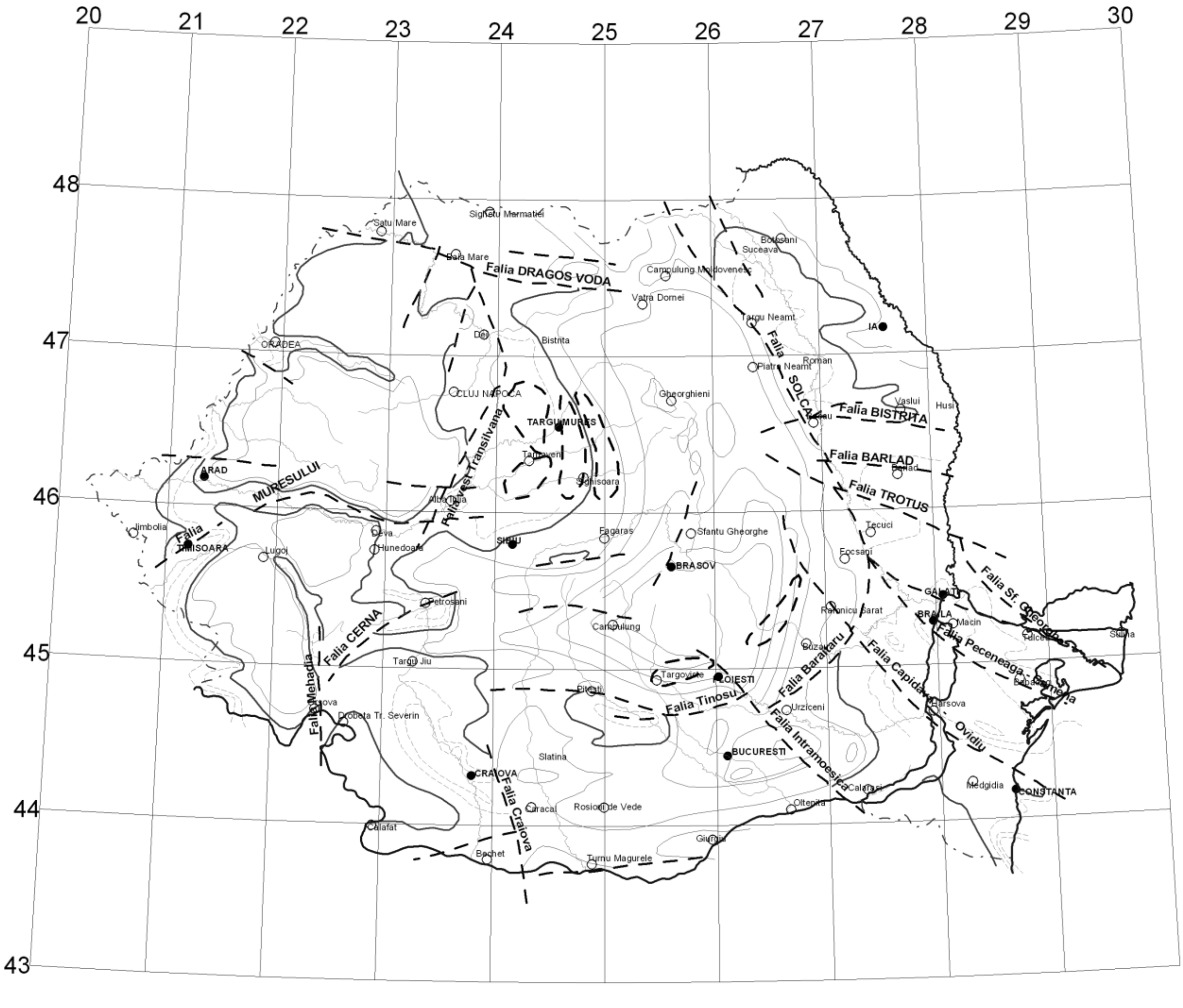

Fig. 1.7. Model of recent vertical crustal movements on the territory of Romania (Zugrăvescu *et al*. 1998).

An important research direction consisted of geodynamic studies based on the interpretation of information provided by seismic prospecting for oil. The research has revealed significant aspects related to the overall geological evolution of the Romanian Black Sea shelf (Chişcan & Damian, 1996), as well as details of the offshore sector of Central Dobrogea (Chişcan & Damian, 1997).

The Malm-Neocomian oil trap structures of the Moesian Platform were also studied (Damian, 1998). Specific research were carried out on the seismic wave velocities in the East Carpathian formations (Damian, 1999), and related to the spatial-temporal evolution of the Vrancea area (Zugrăvescu & Damian, 1999; 2001).

Damian and Zugrăvescu (2002) published a synthesis of the geodynamics of the NW Black Sea inland, with possible consequences on the Vrancea seismogene zone. Damian (2004) also undertook a study on the geodynamic significance of seismic velocity data from the Transylvanian Depression and the Pannonian Depression. A year later, Damian and Zugrăvescu (2005) addressed a similar study to East Carpathians and related foreland (Damian & Zugrăvescu, 2005).

The same authors (Zugrăvescu & Damian, 2006) made observations on the dynamics of the Intramoesian Fault based on the study of seismic surveys results.

Study of geophysical well logs has allowed the development of research on cracked/ fractured zones in the Earth's crust (Zugrăvescu *et al*., 1999) and hydrocarbon migration (Negoiță *et al*., 2000).

The elastic properties of the geological formations within the Căldăruşani–Tulnici geodynamic polygon have also been studied (Zugrăvescu *et al*., 2001).

The strain in the Earth's crust has been another key area of investigation (Zugrăvescu & Polonic, 1997). An overview of the strain echoes in boreholes deformation was also published by Zugrăvescu *et al*. (2000).

The current state of stress in Transylvanian Depression was subject to another study based on the interpretation of borehole logs (Negoiță *et al*., 2007). Another similar study had addressed the East Carpathians area (Polonic *et al*., 2005a).

A special mention should be made for the applied research carried out. For example, recent dynamics of tectonic blocks in the neighbourhood of some major hydro technical facilities were analysed (Polonic *et al*., 2005b), and the possibilities offered by geophysical logs in estimating the magnitude of local anthropogenic seismicity induced by hydrocarbon exploitation in 15 Moldavian oil fields were explored (Negoiță *et al*., 2014–2015).

2. TECHNICAL FACILITIES

2.1. INSTRUMENTATION

To create the necessary framework for achieving the research objectives, it was first necessary to create and/or update the technical/material base. Within the frame of some projects funded outside resources provided by the Romanian Academy, SEDD succeeded to acquire specific equipment for planned research:

– for geodetic observations: two Leica total stations (TCR and TC series) with an accuracy of 2 ppm in distance determination, and a Leica DNA 003 digital level with an accuracy of 0.2 mm/km of levelling;
– for gravity observations: the first relative Scintrex CG5 – AUTOGRAV gravimeter in Romania, credited with a sensitivity of 1μGal, and assisted by a microprocessor for the management and preliminary data processing (e.g., data storage and statistical analysis of observations, automatic application of instrumental corrections like reduction of long-term drift and terrestrial tides, automatic computation of averages for pre-set time intervals);
– for observations on the geomagnetic field: a proton Geometrics GX-856 magnetometer having a sensitivity of 10^{-10} Tesla, and the first Scintrex SM-5 NAVMAG magnetometer-gradiometer in our country, credited with a resolution of 10^{-12} Tesla.

For office activities, personal computers and peripherals, along with the necessary software, including licenses for Windows platforms, standard programs such as Microsoft Office, MATLAB, and CorelDraw, as well as professional packages from Golden Software, such as SURFER and DIDGER. These packages are intended for processing field data and creating databases. Among the peripherals, mention should be made to scanners (including an A0 device), A4 and A3 printers, and a HP A0 plotter.

For advanced processing and interpretation of data, the GEOSOFT Oasis software package, currently employed by national geological services worldwide, has been purchased, along with the GM-SYS 3D for modelling potential field sources. The package has been later enhanced with the Geosoft VOXI Earth Modelling™ interface, a cloud technology that exploits the online capabilities of the Windows Azure cloud.

The application enables geomagnetic or structural and density gravity inversions, which are particularly useful in the valorisation of gravimetric and geomagnetic data by helping to create three-dimensional interpretative models.

A special mention is due to the achievement of the high-speed supercomputer, through EU funding. The SEDD supercomputer is a parallel computing system, made of three main components: (i) HPCC (High Performance Computing Cluster) consisting of 1344 computing cores, a Panasas storage capacity of 40 TB and a Q-logic InfiniBand data transmission bus that ensures a total computing speed of 40 Gb/s, (ii) HPVC (High Performance Visualisation Cluster) consisting of 10 visualization nodes equipped with ATI FirePro V3700 video cards, and (iii) an additional GEOWALL unit (integrated and interactive 3D/4D visualization system of geodynamic models).

It was Professor Dr. Vlad Manea from the National Autonomous University of Mexico (UNAM), who provided valuable guidance for design and construction of the whole computing system.

2.2. RESEARCH INFRASTRUCTURE

Two categories of facilities have been created to carry out observations on the Earth's dynamics:

– permanent geodynamic stations (observatories);
– networks of temporary stations for repeated observations.

2.2.1. Underground gravity lab

Located in the basement of the main building of IGSSS headquarter, the laboratory is designed to record terrestrial tides, and monitor distortions into the temporal evolution of the gravity field provoked by worldwide major seismic events.

Between field campaigns, the SCINTREX CG5 gravimeter was installed on a reinforced concrete pillar buried 1.5 m and separated from the laboratory floor to avoid the transmission of building vibrations (Fig. 2.1). The meter continuously records the time evolution of gravity, providing every minute averages of the gravity observed together with the horizontality parameters of the instrument, and corrections for the terrestrial tide.

Fig. 2.1. Scintrex CG5 gravimeter #40387operated on the pillar of the gravity laboratory.

2.2.2. Başpunar Observatory

The permanent geodynamic station, located in the Fântâna Mare village, Tulcea county, conventionally called Başpunar Geodynamics Observatory (BGO), was designed and built up in order to monitor deformation of the crust along the Peceneaga-Camena Fault (PCF), the NE edge of the Moesian Plate, separating the cratonic area of Central Dobrogea from the structures of the fold and thrust mobile zone of North Dobrogea (Fig. 2.2).

The track of the fault in the BGO area was identified following detailed geological research conducted by Professor Emil Grădinaru from the University of Bucharest. The location, along with the active nature of the contact, were documented by detailed geomagnetic investigations (Besutiu *et al.*, 2014), and mapping of Rn222 emissions (Fig. 2.3) originating from large depths (Cosma *et al.*, 2014).

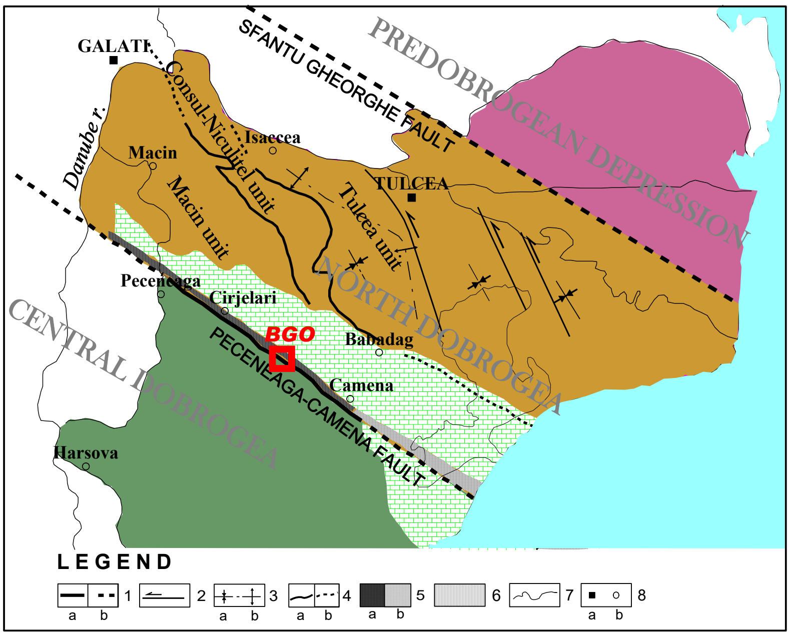

Fig. 2.2. Tectonic setting of the Başpunar Geodynamics Observatory 1 faults (a, cropping out; b, hidden); 2, strike-slip faults; 3, structural axes; 4, contacts between units of Northern Dobrogea (a, exposed; b, hidden); 5, Camena-Cârjelari Formation; 6, post-tectonic cover; 7, rivers, 8, localities (a, main; b, secondary).

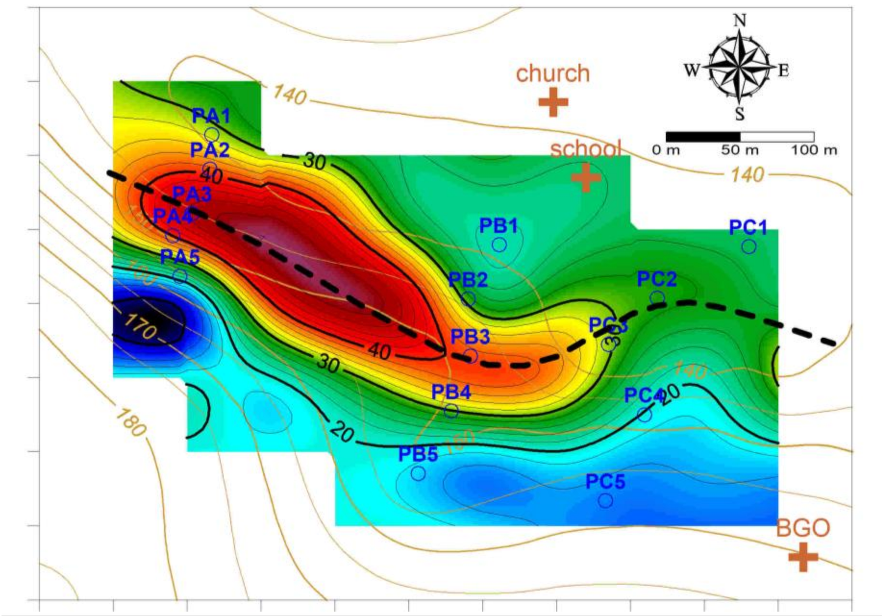

Fig. 2.3. Radon anomaly outlined along the PCF in the BGO area (based on raw data of Cosma *et al.*, 2014).

Basically, the Başpunar observatory consists of two Leica total stations located on the southern flank of the PCF, which observe and record the distance to reflectors located on the northern flank of the fault (Fig. 2.4).

Two reinforced concrete pillars, to their turn fixed in a concrete platform embedded in the Green Schist series of Central Dobrogea, provide stability to the total stations. A lightweight construction shelters the entire assembly.

Data acquisition use a software especially designed to exploit to the maximum the metrological capabilities of the instruments, with routines created and implemented by Dr. Marin Plopeanu, university lecturer at the Faculty of Geodesy of the Technical University of Civil Engineering in Bucharest, within an inter-institutional collaboration (Besutiu *et al*., 2013). The software allows for measuring the distance of about 350 m between the total station and the reflector with an accuracy of about 0.5 mm.

To allow for applying corrections for mitigating the influence of atmospheric factors (pressure, temperature, and humidity), BGO has its own meteorological station that permanently measures and records atmospheric parameters.

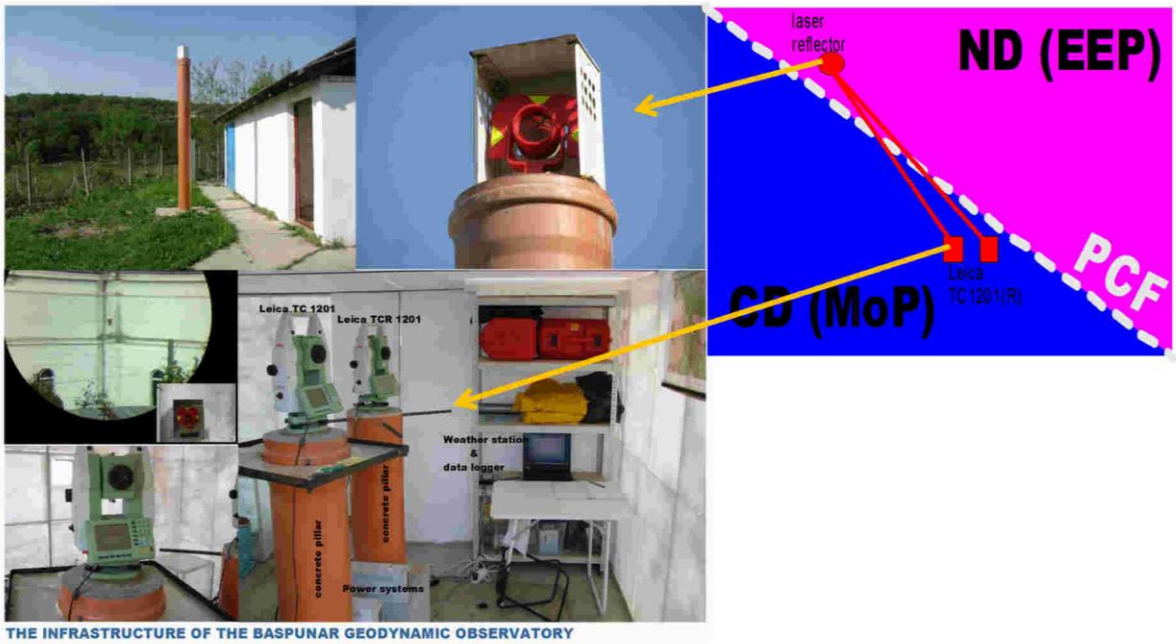

Figure 2.4. General appearance and operating scheme of the BGO.

Two laptops control the entire data acquisition process (geodetic and meteorological) and enable the storage and periodic transmission of data to the SEDD headquarters in Bucharest, where they are daily processed and interpreted (Zlăgnean *et al*., 2022–2023).

2.2.3. National network for geodynamic monitoring

Romania's territory hosts three major lithospheric compartments: the SW edge of the East European Plate (EEP), the northern segment of the Moesian Microplate (MoP), and the Intra-Alpine Microplate (IaP) that includes the Transylvanian Depression (Constantinescu *et al*., 1976; Besutiu, 2003).

They are separated by lithospheric contacts with surface echoes as well-known major faults: the Peceneaga-Camena Fault (PCF), between MoP and EEP; the Trans-Getic Fault (TGF), between MoP and IaP; and the south-easternmost end of the Trans-European Suture Zone (TESZ), which separates IaP from EEP.

The three lithospheric compartments, with different thicknesses (150–160 km for EEP, 120–130 km for MoP, and 80–90 km for IaP) meet in the geodynamic active Vrancea zone, where magneto-telluric soundings have revealed the asthenosphere at about 200 km depth (Stănică *et al*., 1986).

The network for geodynamic monitoring of the national territory was designed to cover the contacts between the three lithospheric compartments, and the Vrancea seismic area (Fig. 2.5).

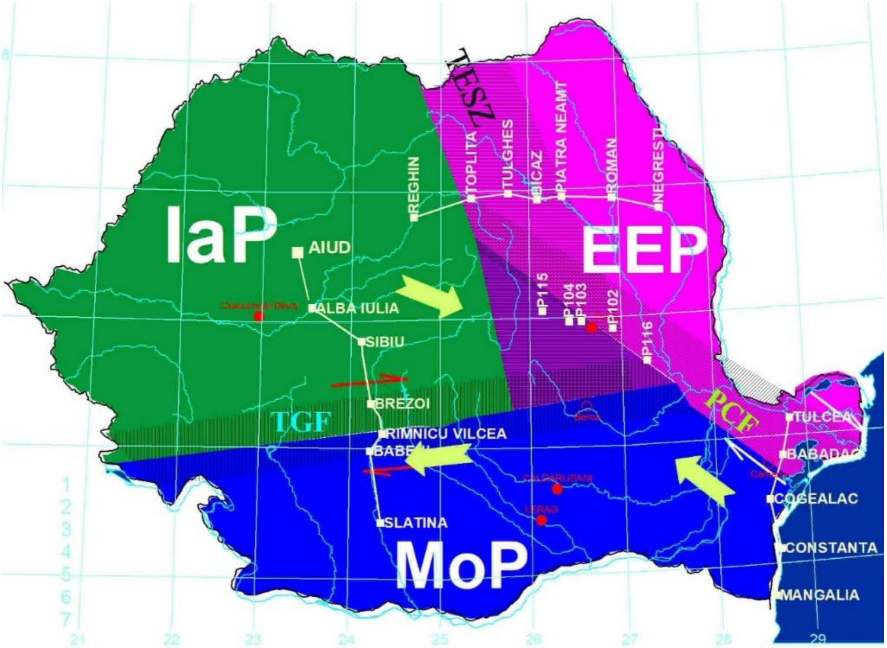

Figure 2.5. Lithospheric compartments and the design of the network for geodynamic monitoring of the Romanian territory.

Each base-station of the network consists of a reinforced concrete pillar (weighing over a ton) grounded about 1.5 m and exposing at the surface a cube of 0.5 m side with a flat horizontal top, providing reproducibility conditions for repeated gravity and/or space geodesy (GPS) observations. For GPS determinations, a special device for centring the GPS antenna (CERGOP 2 standard) was implemented on the pillar's top. The pillar bears an identification plate, and its location is described in a special catalogue that includes coordinates and detailed local information.

Figure 2.6. The Romanian geodynamic network benchmarks. The arrow marks the device for centring the GPS antenna.

2.2.4. Modernization of the micro-polygon no. 1 Tulnici–Valea Sării–Vrâncioaia

With the acquisition of its own gravimeter, SEDD updated the micro-polygon no. 1 for adding systematic gravity observations to the geodetic ones. Therefore, each levelling station within the polygon was equipped with a concrete benchmark (0.5 × 0.5 × 0.5 m), for providing stability to repeated high-accuracy gravity observations with the Scintrex CG5 gravimeter (Fig. 2.7).

Figure 2.7. Scintrex CG5 AUTOGRAV #40387 gravity meter operated on a gravity benchmark within the Tulnici–Valea Sării–Vrâncioaia micro-polygon.

The gravimetric plates were installed in the immediate vicinity of the buried levelling benchmarks to jointly exploit gravity and geodetic data (Fig. 2.8).

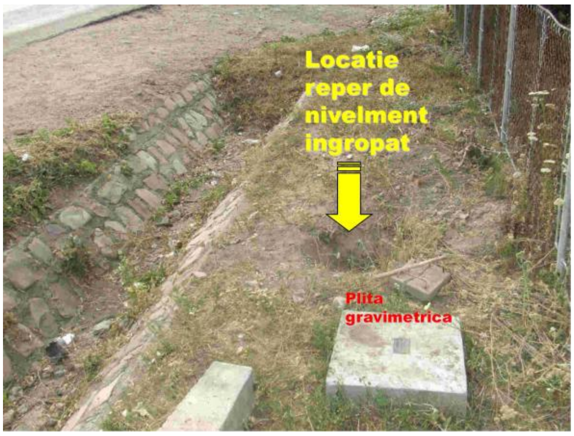

Figure 2.8. Location of levelling benchmarks and gravimetric plates within micro-polygon no. 1.

3. MAIN RESEARCH DIRECTIONS

At the beginning of the 21st century, SEDD focused activity mainly on the Vrancea active geodynamic area for answering requirements of the Romanian Academy's priority program "*Complex geophysical research in geodynamic active areas, with special attention to the Vrancea area"*.

Among the efforts targeting the causal relationship between the structure and dynamics of the Earth's interior and seismicity, mention should be made to the following research directions:

– seismology;
– deformations of the Earth's crust;
– space-time structure and evolution of the gravity field and the geomagnetic field;
– implementation of numerical models for studying the structure and dynamics of the Earth's interior;
– regional tectonic setting of active geodynamic areas;
– numerical simulation of thermodynamic processes within the upper mantle.

3.1. SEISMOLOGICAL STUDIES

Seismological research has focused particularly on the active Vrancea zone of intermediate-depth earthquakes. Crust seismicity, both in front of the Carpathian bending zone and throughout the rest of the country, was also studied. Additionally, sometimes global seismic activity was also subject to research, especially when it might affect the Romanian territory.

At a global level, similarities and differences have been highlighted between the Vrancea and Hindu Kush-Pamir seismogenic zones (Zlăgnean & Besutiu, 2007).

Overall, seismological studies began with the preparation of earthquake bulletins by compiling seismic data provided by authorized bodies, such as INCDFP, EMSC, GEOFON Potsdam, and ISC, aiming to reduce errors in earthquake localization, hypocentre depths, magnitude, and parameters of the earthquake mechanisms.

The stress regimes were visualized through maps representing both the distribution of the tectonic stress regime according to the rupture and the azimuths of the maximum horizontal stresses, as well as through Frohlich ternary diagrams that systematize the mechanisms in focus at a local or regional scale according to the type of rupture. Stereonet and Rose diagrams highlighted the azimuths of the principal horizontal stresses, the azimuths and inclinations of the nodal planes, slip lines, and principal stress axes.

The seismic energy released was analysed quantitatively on an annual basis, taking into account the characteristics of the seismic zones considered. For the analyses performed and the graphic representations, specific computing routines were used, such as WinTensor (Delvaux & Sperner, 2003) and the Wolfram notebook / Demonstrations Project – Earthquake Focal Mechanism (Scherbaum *et al.,* 2011), but also standard programmes such as ArcGIS Pro and Surfer, as well as online routines like CASMO – Create A Stress Map Online.

Complex research has been undertaken on the impact of Vrancea and neighbouring area seismicity on the chemistry of some springs (e.g., Mitrofan *et al*., 2009; Mitrofan *et al*., 2010a; Mitrofan *et al*., 2010b), and the relationship between temperature and characteristics of the earthquake focus (Mitrofan *et al*., 2010c).

In collaboration with researchers from other teams in the institute, it is worth mentioning an alternative geodynamic model to explain Vrancea intermediate-depth earthquakes (Mitrofan *et al*., 2014, 2016).

A possible correlation has been highlighted (Mitrofan & Anghelache, 2024) between moderate earthquakes located at depths below 160 km and major earthquakes in the depth range 90–120 km. It was even speculated that the deeper moderate earthquakes are possible precursors of those located above them.

Seismic hazard estimate is an important component of seismic risk assessment (e.g., Balan *et al*., 2014; Anghelache *et al*., 2018a).

Some authors (Anghelache & Osiceanu, 2010; Anghelache, 2017) proposed seismic risk scenarios for our country in the event of a major Vrancea earthquake with a magnitude of 7–7.5.

Research on the effects of earthquakes on karst aquifers and springs that supply thermal baths led to conclusions regarding the seismic hazard associated with them (Boştenaru *et al*., 2023).

The possible radionuclides pollution of groundwater in the Cernavoda nuclear plant area was also analysed from the perspective of seismic risk in the event of a major Vrancea earthquake (Anghelache *et al*., 2014; Anghelache *et al*., 2018b).

3.2. STUDIES OF THE CRUST DEFORMATIONS

A brief review of geodetic research previously conducted in Romania for geodynamic purposes was published at the beginning of the 21st century (Besutiu *et al*., 2006c). Crust deformation of the Vrancea region has been subject to research at a regional scale through geometric levelling and space geodesy, within various national/ international efforts like CERGOP project (e.g., Rus *et al*., 2005, 2006, 2009; Ghiţău, 2006).

With the efforts concentrated on the crust and intermediate depth seismicity zone within East Carpathian bending zone, and the adjacent foreland, SEDD carried out geodetic research, within the priority program coordinated by the Romanian Academy, in two main directions:

(i) vertical deformations of the crust in the epicentres area of the Vrancea intermediate earthquakes and

(ii) horizontal deformations of the crust in geodynamically active areas.

3.2.1. Vertical deformations of the crust

The study of vertical crustal deformations in the epicentres area of Vrancea intermediate seismicity was based on repeated high-precision geometric levelling in micro-polygon no. 1, carried out by SEDD or other research organizations as part of collaborative projects.

Figure 3.2.1 illustrates levelling works conducted by SEDD using the own Leica DN-003 level.

Figure 3.2.1. Levelling works carried out by SEDD members
in the geodynamics micro-polygon no. 1.

The infrastructure of the micro-polygon no. 1 has been also systematically used by students of the Faculty of Geodesy in carrying out annual practice (Fig. 3.2.2).

Following the observations, it is worth mentioning the overlap of two trends in the evolution of crustal movements: an overall long-term uplift of the mountain sector relative to the neighbouring area, determined by the crust elastic rebound, following the denudation and erosion of the Carpathian chain, and a series of local, short-term actions, characterized by different durations, amplitudes, directions and speeds from one moment to another, as consequence of stress changes (Zlăgnean *et al*., 2001, Zlăgnean *et al*., 2006).

Repeated geometric levelling surveys within micro-polygon No. 1 seem to indicate distinct dynamic regimes for the northern and southern parts of the area, separated by a central alignment oriented approximately WNW-ESE (Fig. 3.2.3).

Figure 3.2.2. Students of the Faculty of Geodesy performing geometric levelling works within the geodynamic micro-polygon no. 1.

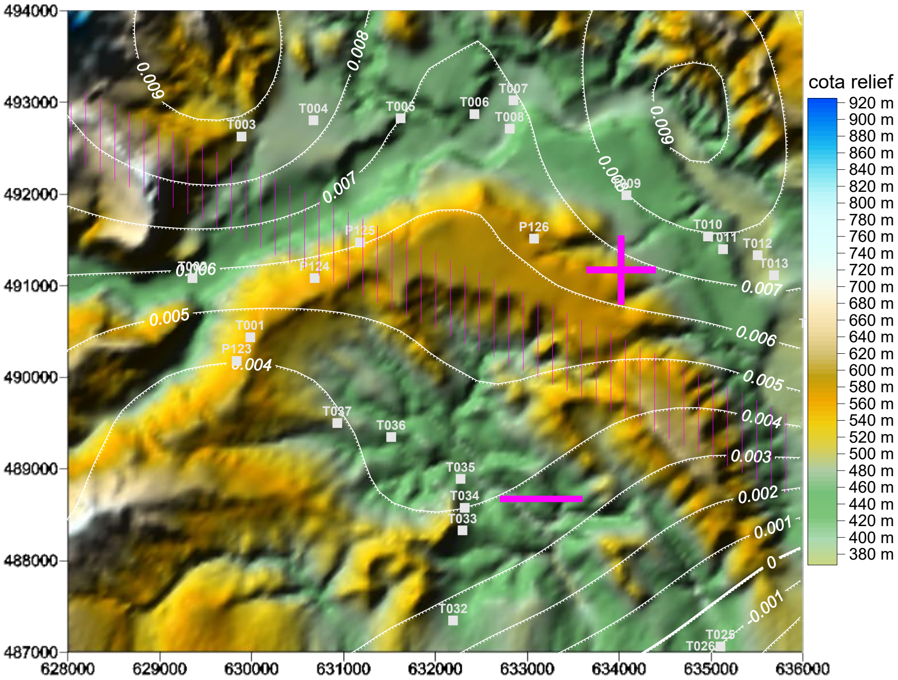

Figure 3.2.3. Surface topography (in colours) and vertical crustal deformations (contours in metres) within micro-polygon no. 1 recorded between 2007–2008 (Besutiu *et al*., 2008b).

A similar behaviour was also detected by consecutive observations campaigns, conducted before and after a significant earthquake occurred in the Vrancea area (Fig.3.2.4).

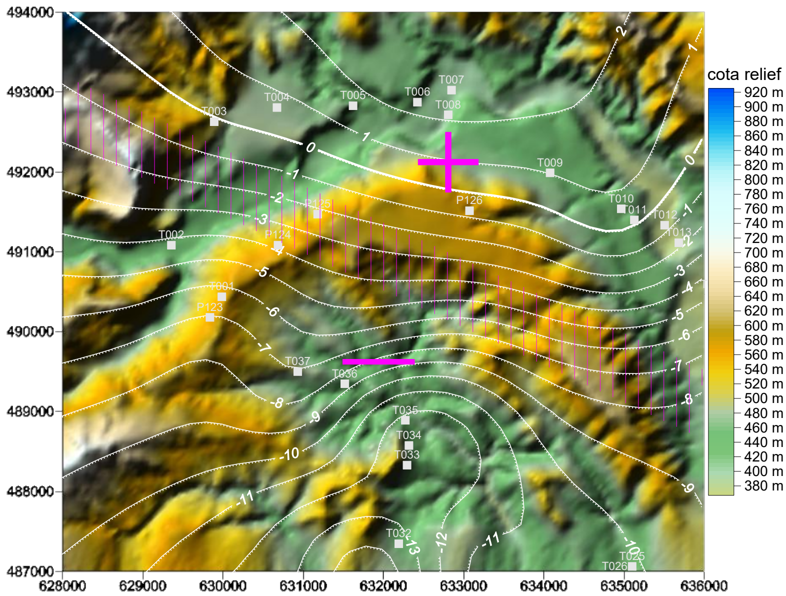

Figure 3.2.4. Surface topography and vertical crustal deformations in micro-polygon no. 1 associated with an earthquake with magnitude Mw 6.0. (Besutiu *et al*., 2008b).

The different geodynamic evolution on either side of the mentioned alignment suggests the existence of a deep tectonic accident, which split the micro-polygon no.1 into two distinct tectonic compartments. The alignment overlaps a possible extent towards the Carpathians of the PCF (mentioned by Ludovic Mrazec since the beginning of the last century), which seems confirmed by its echo in a filtered image of the geomagnetic anomaly (Fig. 3.2.5) in the area at the East Carpathian bending zone (Besutiu & Zlăgnean, 2010c).

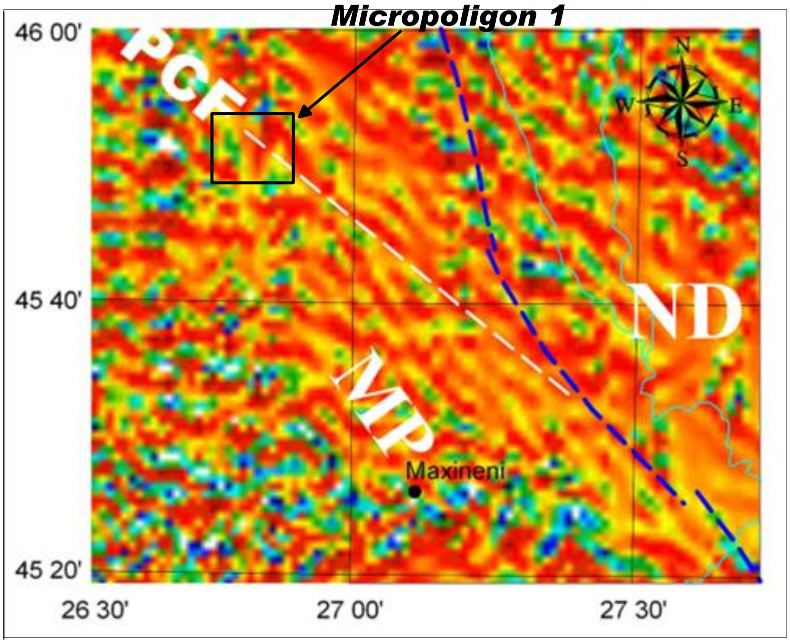

Figure 3.2.5. Imprint of a hidden fault crossing micro-polygon no. 1 in the horizontal gradient of the geomagnetic anomaly. The current accepted path of the PCF is indicated by the dashed blue line. The discontinuity marked by the dashed white line marks a fault associated with the presumed extent of the PCF to the NW. MP, Moesian Platform; ND, North Dobrogea (after Besutiu & Zlăgnean, 2010c).

3.2.2. Horizontal deformation of the crust

3.2.2.1. GNSS determinations

With the increase in accuracy of the space geodesy, reaching the level required by geodynamic studies, IGSSS concluded partnerships with the Department of Geodesy of the Faculty of Geology and Geophysics at the University of Bucharest, as well as with the Faculty of Geodesy within Technical University for Civil Engineering Bucharest, partnerships within which measurement campaigns were carried out both in the active geodynamic Vrancea area and, later on, within the national geodynamics network.

The first GPS observations in the Vrancea seismic zone date back to the period of 1992–1993 (Neuner, 1993; Schwieger *et al*., 1994; Rus *et al*., 1995). However, the insufficient precision for the geodynamic studies did not allow for conclusive results.

Since 2006, SEDD has had a close collaboration with the Faculty of Geodesy following the partnership within the INDEGEN project (*Integrated research on the genesis of intermediate-depth intracontinental earthquakes in the Vrancea area*). Within the project, the geodesy partners made a series of observations with professional GNSS stations on the national geodynamics network benchmarks (Fig. 3.2.6).

Observations conducted in two successive GPS campaigns in 2007 and 2008 (Fig. 3.2.7) unveiled overall trends in the movement of the lithospheric compartments within our country's territory.

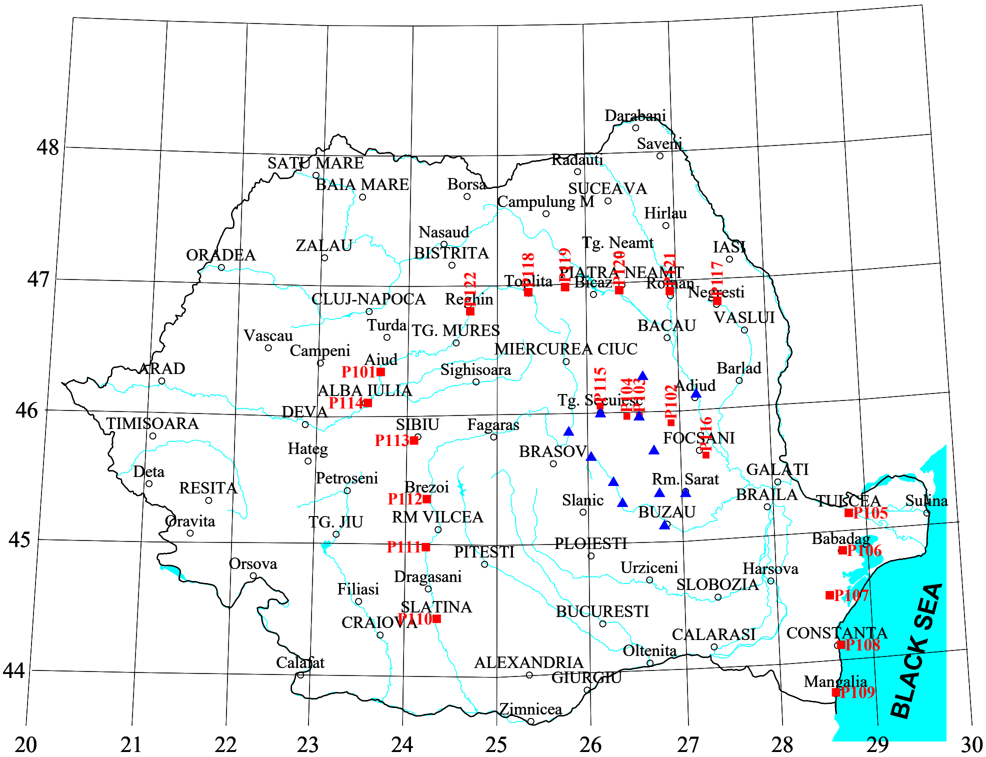

Figure 3.2.6. Location and code of the pillars of the national geodynamics network on which GPS determinations were carried out within the INDEGEN project.

Fig. 3.2.7. GPS observations conducted on the P115 Sânzieni benchmark.

Figure 3.2.8 presents the motion vectors determined in a reference system in which the permanent station in Bucharest (BUCU) is considered in motion, according to the ITRF05 model.

Overall, vectors confirm the overall NE direction of the Eurasian Megaplate motion.

Along the Slatina–Aiud line, the slightly divergent direction of the vectors on either side of TGF seems to indicate a slight compression, suggesting a right-lateral transpressive nature of the contact between MoP and IaP.

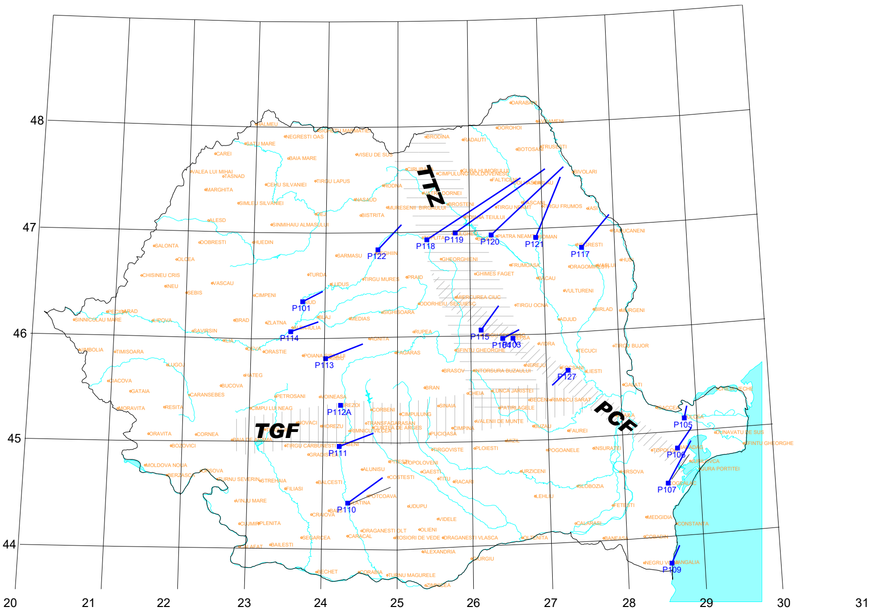

Fig. 3.2.8. Motion vectors determined in the national geodynamics network, as referenced to the moving permanent GNSS station Bucharest, according to ITRF05 (after Besutiu *et al*., 2008b).

In contrast, along the profile crossing the PCF, the direction of motion remains unchanged in the two compartments, which advocates for the pure strike-slip character of the contact.

Along the line crossing the TESZ, the motion vectors seem to indicate a slight westward compression, in agreement with stress information provided by the study of boreholes breakout (Negoiță *et al*., 2007).

For the Vrancea area, vectors exhibit a large dispersion in direction and intensity, which is difficult to interpret.

3.2.2.2. Monitoring PCF dynamics

Another direction of geodetic research has been the monitoring of PCF dynamics, the lithospheric contact between MoP and North Dobrogea thrust and fold belt, a transition zone to EEP.

In an attempt to determine a possible connection between the horizontal movements in the Carpathian foreland and the alleged sinking of the lithosphere that generates Vrancea earthquakes, the BGO was used to monitor slip rate along the PCF as *a proxy* for the strain change induced by the Black Sea microplate into the NW inland.

There have been years of BGO improvements in both the infrastructure and methodology for recording, storing, transmitting, and processing data. That has been subject to several scientific communications and papers (Besutiu & Zlăgnean, 2009a, b; Besutiu and Zlăgnean, 2010a, c; Besutiu *et al*., 2013; Besutiu *et al*., 2014; Zlăgnean, 2022; Zlăgnean & Besutiu, 2024; Pomeran & Zlăgnean, 2024).

Even since the beginning, it became evident that atmospheric factors (especially temperature) had a strong influence on the measurements. Therefore, specific corrections are applied to the observed distance, taking into account the influence of atmospheric factors upon the speed of electromagnetic waves.

Additionally, to avoid the effect of direct insolation, strongly affecting the quality of measurements, and the incomplete compensation through temperature corrections, night recordings only, collected between sunset and sunrise, were selected for interpretation.

As mentioned above, BGO was meant to monitor changes in the intensity of tectonic forces acting within the eastern MoP and Vrancea area. The main idea (see the tectonics section of this paper for detail) is that the platform compartments are pushed by the Black Sea microplate, and advance together towards Carpathians, held by frictional forces. However, when tectonic forces exceed the frictional threshold, the compartments may slip relative to each other, generating earthquakes in the brittle part of the crust along the contacts (Besutiu, 2001b).

Zlăgnean (2022) studied the correlation between the annual average slip along PCF and the annual seismic energy released by intermediate and crustal earthquakes, during the 2014–2022 timespan. Whether intermediate earthquakes do not show a full correlation with PCF behaviour (there is a time lag between fault acceleration and the occurrence of the seismic event), for significant crustal events (of magnitude M5+) the correlation seems obvious. As expected, the crustal seismicity of the North Dobrogea mobile zone is the most intense, and better correlates with the slip rate along the PCF. Some examples of such correlations are shown in Figures 3.2.9–3.2.11.

Figure 3.2.9 presents the PCF behaviour during the 2013 Galaţi-Izvoarele seismic swarm. BGO records show several stages of the fault dynamics: (i) slight right-lateral slip; (ii) fault lock; (iii) high right-lateral acceleration followed by abrupt left-lateral slip; (iv) short fault lock followed by (v) a came back to the slight right-lateral behaviour. The most intense seismic activity was triggered during the high right-lateral acceleration, interpreted in terms of a tectonic stress increase, which activated the seismic prone structure in front of the Pechea basement horst.

The other two examples illustrate episodes of earthquakes occurred within the Moldavian Platform and eastern MoP.

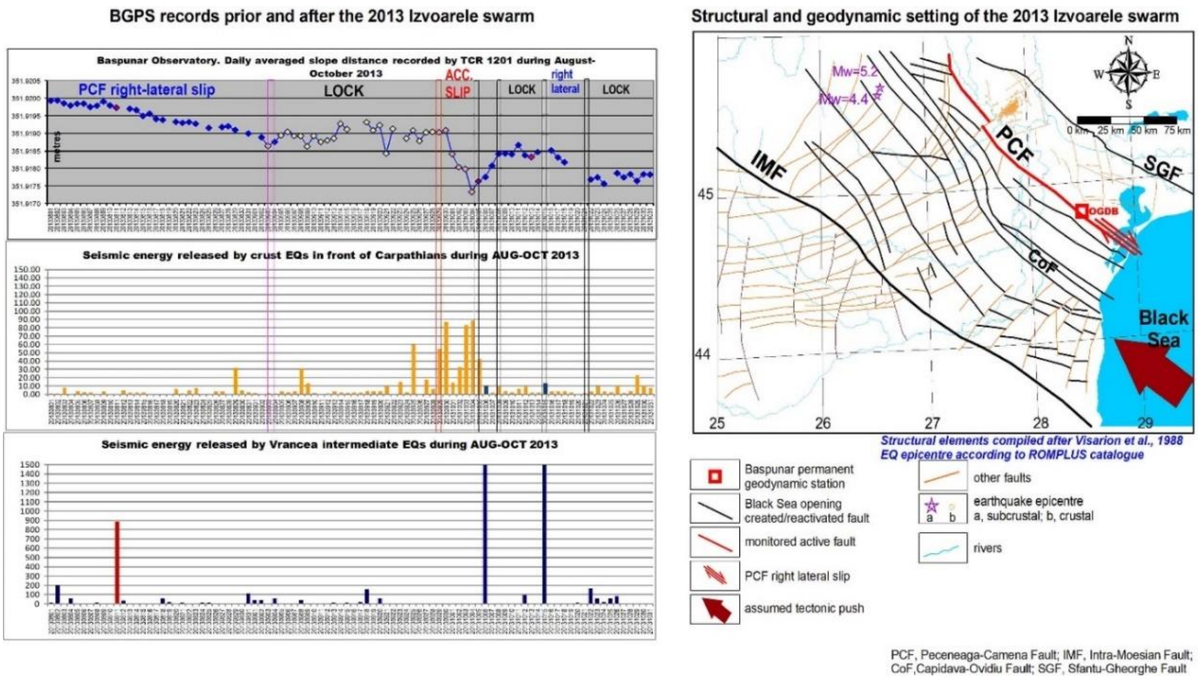

Figure 3.2.9. BGO recordings before and after the 2013 Izvoarele earthquake swarm (Besutiu *et al*., 2019 b).

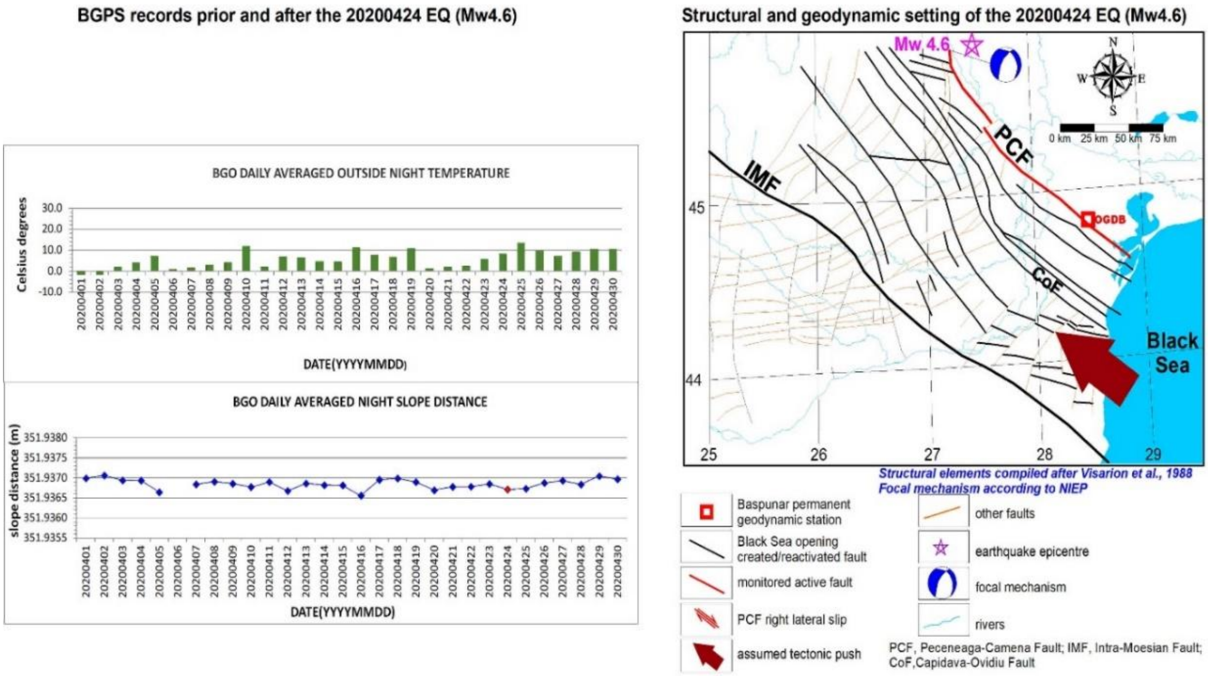

Figure 3.2.10. BGO records associated with the Mw 4.6 earthquake of 24.04.2020.

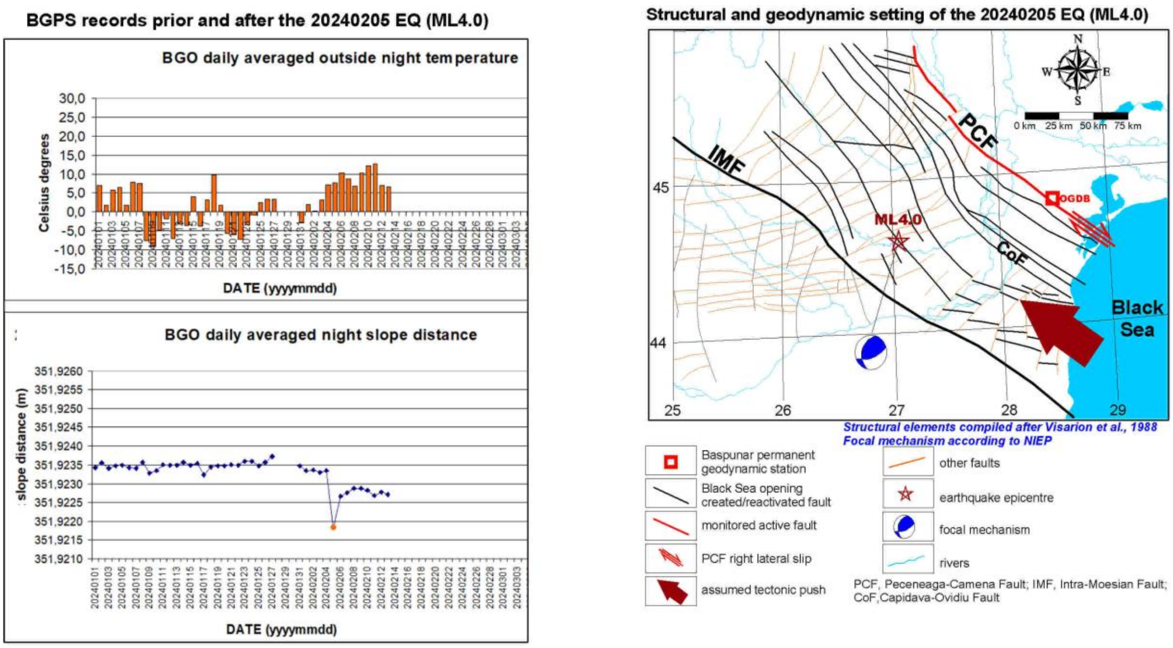

Figure 3.2.11. BGO records before and after the ML 4.0 earthquake of 06.02.2024.

It must be stressed that in case of the event triggered within the Moldavian Platform, a PCF slip acceleration was not recorded at BGO. The fact reveals limits of the adopted methodology. Monitoring the PCF does not always allow for unveiling changes in the stress state in the foreland, because increase of the Black Sea microplate thrust may be accommodated as well by triggering slip along other foreland faults.

To conclude, whether any acceleration along the PCF indicates an increase in the tectonic stress, not every amplification of tectonic forces has a direct echo in the PCF behaviour, as it can activate other major tectonic contacts in the foreland.

Certainly, the system could be improved by designing and installing a permanent network of GNSS stations to monitor all major faults in the Carpathians foreland.

3.3. RESEARCH RELATED TO THE GRAVITY FIELD

3.3.1. General considerations

After acquisition of the Scintrex CG5 AUTOGRAV gravimeter, field observations to complement previous surveys, and maps of the Bouguer anomaly were conducted within confined areas, where seismicity was triggered (Fig.3.3.1), as in the case of Galaţi-Izvoarele (Besutiu *et al.*, 2019a), or to a broader extent (Fig. 3.3.2), as was the case of studying the Neogene-Quaternary volcanism within East Carpathians (Besutiu *et al.*, 2016b; Seghedi *et al.*, 2019).

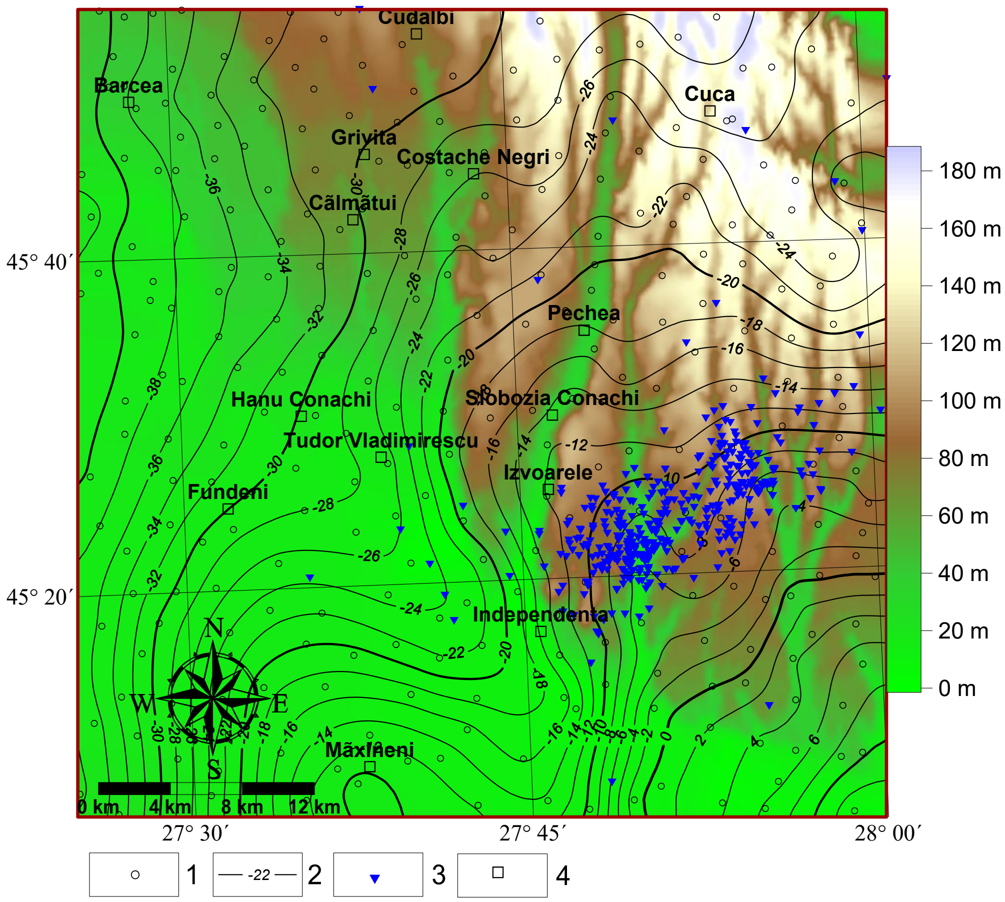

Figure 3.3.1. Bouguer anomaly in the epicentres area of the Galaţi-Izvoarele crustal earthquake swarm (Besutiu *et al*, 2019 a). 1, gravity station; 2, isogal (in mGal); crustal earthquake epicentre; 4, human settlement.

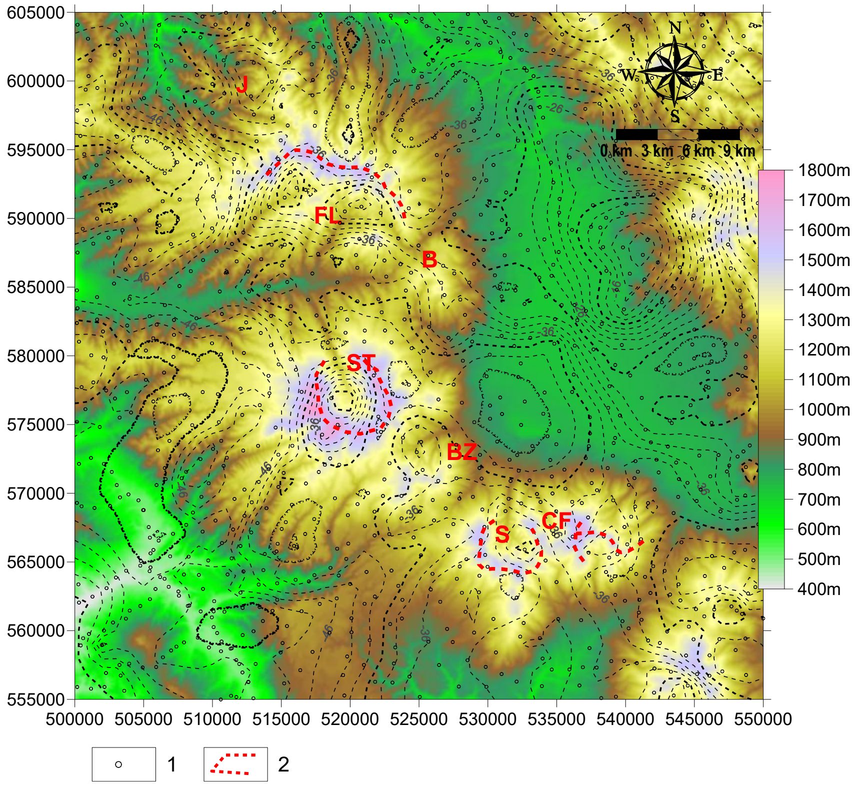

Figure 3.3.2. Bouguer anomaly in the Gurghiu Mountains area superimposed on the relief of the observation surface. Reference density: 2670 kg/m [3.] 1, gravity station; 2, volcanic structure outline.
J, Jirca; FL, Fâncel–Lăpușna; B, Bacta; ST, Seaca–Tătarca; Bz, Borzont; S, Șumuleu; C, Ciumani–Fierăstraie (after Besutiu *et al*., 2016b).

To facilitate interpretation, gravimetric information was often complemented by data about the lithospheric geomagnetic field in the respective area (Fig. 3.3.3).

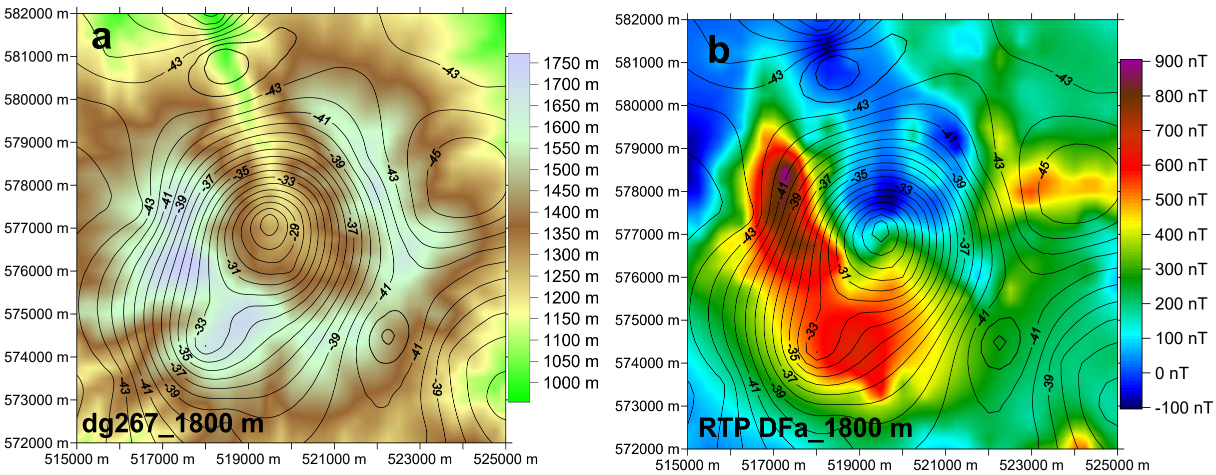

Figure 3.3.3. Combined analysis of the Bouguer anomaly superimposed on (a) the topography model and (b) the pole-reduced geomagnetic anomaly, at an altitude of 1800m in the Seaca-Tătarca volcano area (Besutiu & Zlăgnean, 2024a).

3.3.2. Study of the space-time gravity change

3.3.2.1. Vrancea gravity dedicated network

An essential direction among SEDD research is the monitoring of spatial-temporal variations in the gravity field within active geodynamic regions, with a particular focus on the Vrancea area, based on the idea that these variations reflect the dynamics of masses within the Earth's interior. For the Vrancea zone, a special infrastructure was developed, complementing the national network for geodynamic monitoring of the Romanian territory. The Vrancea gravity network is dedicated to the study of non-tidal gravity change within the epicentre area of intermediate earthquakes through high-accuracy repeated determinations (Fig. 3.3.4).

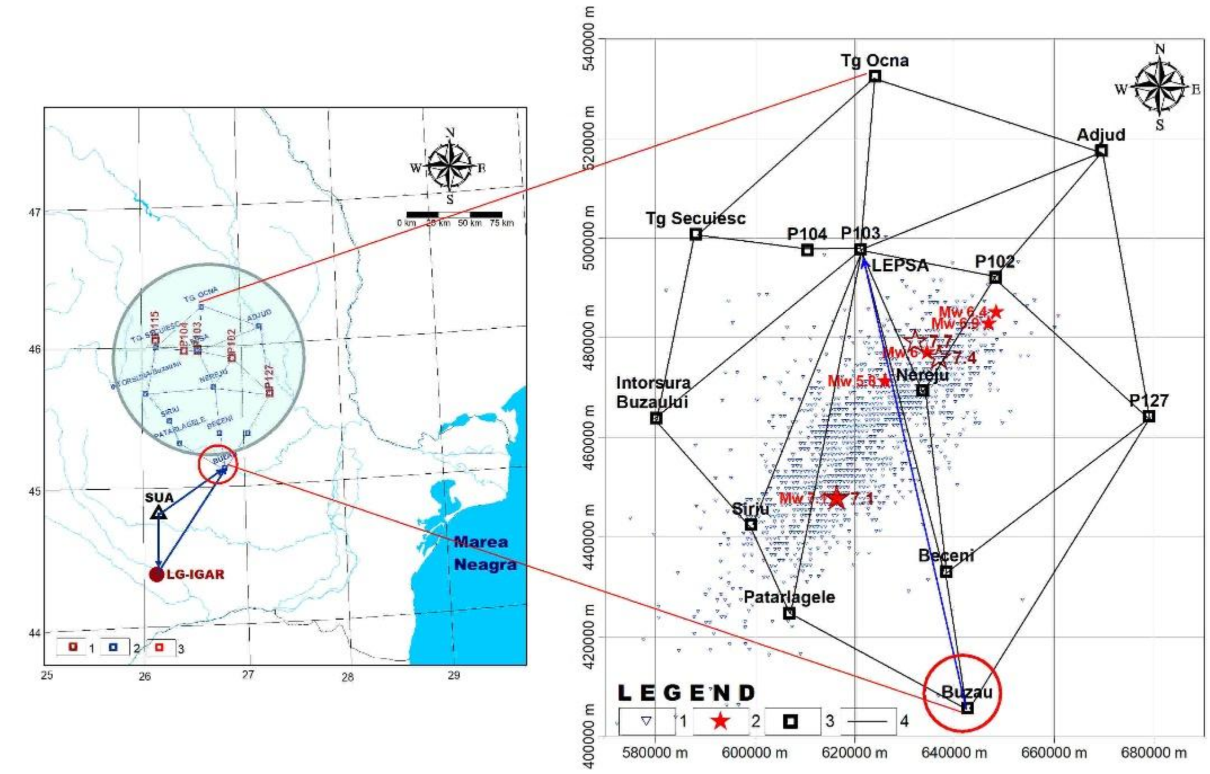

Figure 3.3.4. Location and design of the Vrancea gravity dedicated network (VGDN) and network for absolute gravity transfer. On the left: 1, pillars from the national geodynamics network; 2, stations of the Vrancea dedicated network; 3, additional geodesic-gravimetric pillars; SUA, fundamental gravity station; LG-IGAR, Gravity Laboratory of the SEDD; On the right: 1, upper mantle earthquake epicentre; 2, major earthquake epicentre (M>5); 3 VGDN station; 4, gravity tie.

3.3.2.2. Instruments and methodology

The use of a relative gravimeter requires a network of triangles, which allows for unveiling observations' errors through triangles misclosure, and their adjustment.

To transfer absolute gravity values to each base station of the network, an auxiliary network was added that connects the Buzău VGDN station (located outside the Vrancea active geodynamic zone) to the fundamental gravity point of Romania, located at the Surlari National Geomagnetic Observatory (acronym SUA in the INTERMAGNET network that links worldwide geomagnetic observatories).

The idea of VGDN came after a previous experiment carried out by conducting high-accuracy repeated gravity observations along three lines crossing the main lithospheric contacts on the Romanian territory (Besutiu *et al*., 2006). On each benchmark, absolute gravity values were transferred from both the 2nd order national gravity network (Besutiu *et al*., 1994), which provides gravity values for the 1980 epoch, and the UNIGRACE European network (Besutiu *et al*., 2001c), providing absolute values for the 2000 epoch. In this way, pairs of gravity values separated by about a twenty-year timespan were obtained at each station. Results of the observations on vertical deformations of the crust obtained through geometric levelling along the 1st order national geodetic lines (Popescu & Drăgoescu, 1986) were added to the gravity data.

The experiment outlined a distinct spatiotemporal evolution of gravity within the three lithospheric compartments (Besutiu *et al*., 2004) during the above-mentioned timespan (Fig. 3.3.5).

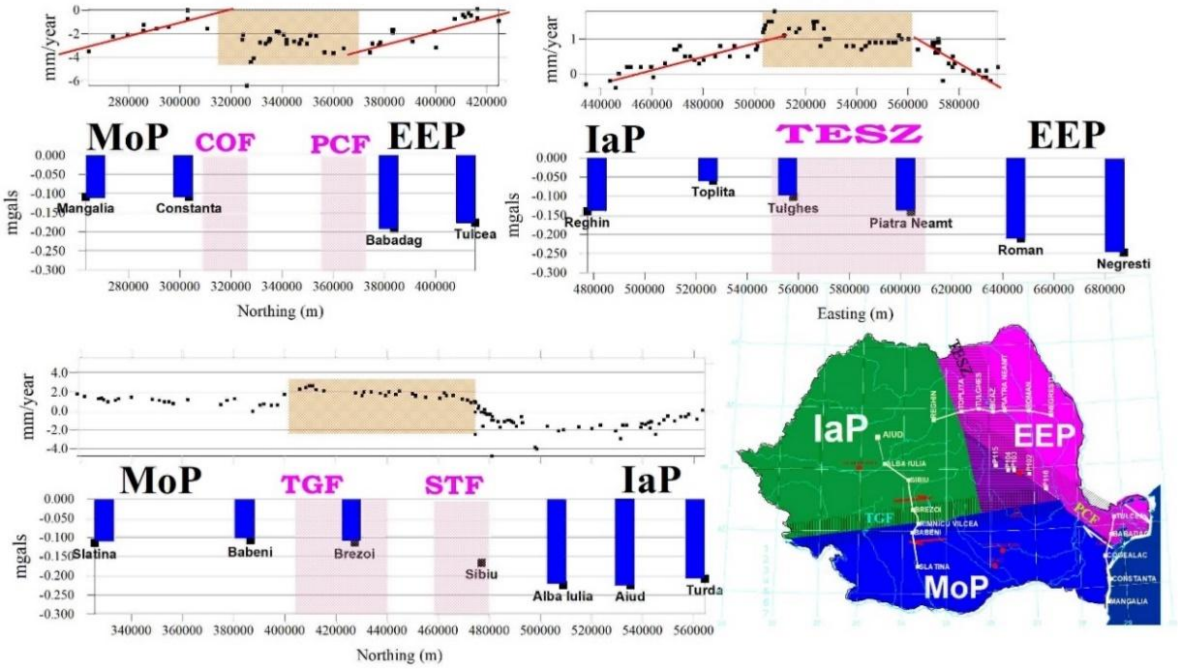

Figure 3.3.5. Gravity change between the epochs 1980 and 2000 (vertical blue bars) and the vertical deformation rate of the Earth's crust along three lines crossing the lithospheric contacts on the Romanian territory (after Besutiu *et al*., 2006). STF, South-Transylvanian Fault.

3.3.2.3. Gravity behaviour within Vrancea zone

In the Vrancea area, the observation of the non-tidal evolution of gravity started by transferring absolute gravity values to each VGDN station, provided by the two previously mentioned reference networks. This process yielded pairs of values that demonstrate how gravity changed in this active geodynamic area over about two decades. Figure 3.3.6 illustrates the obtained results.

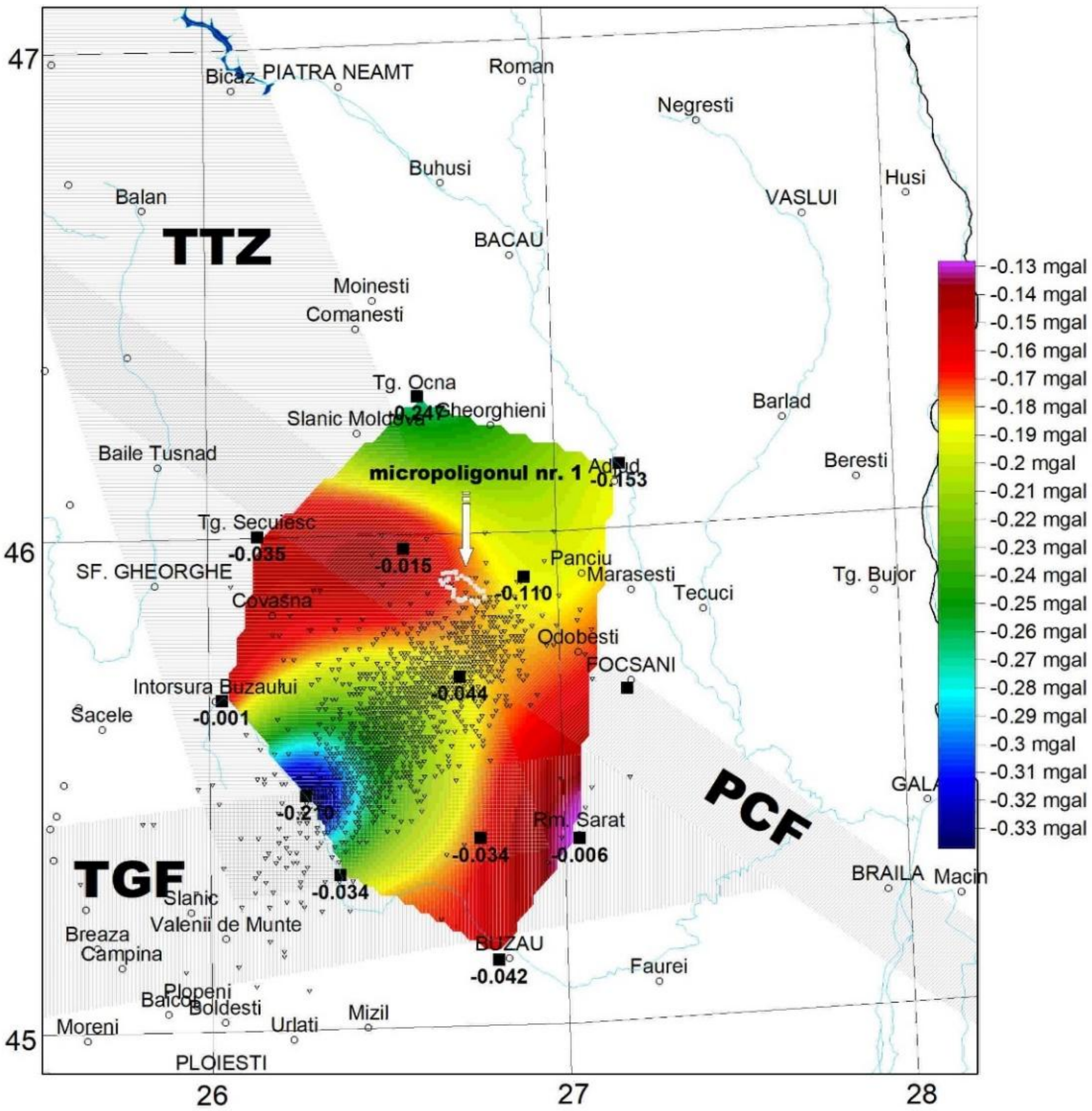

Figure 3.3.6. Non-tidal gravity change in the Vrancea area between the epochs 1980 and 2000. Grey triangles mark epicentres of upper mantle earthquakes triggered during the above-mentioned period (Besutiu *et al.*, 2019b).

In the epicentres area of intermediate-depth earthquakes, an overall gravity lowering exceeding 200 μGal was recorded over a timespan of about 20 years.

In the next step, the results were corrected for the influence of vertical deformations of the crust, as observed in the area during the European CERGOP project (Ghiţău, 2006).

Based on the value of the vertical gravity gradient measured at each VGDN station, and the vertical displacement of the benchmark, a correction was applied to the observed gravity.

The obtained results did not significantly differ from the initial results (Fig. 3.3.7).

It should also be mentioned that gravity lowering in the epicentres area unusually associates with a relative subsidence trend superposed on the overall uplift of Carpathians, as a consequence of isostatic rebound after denudation and erosion.

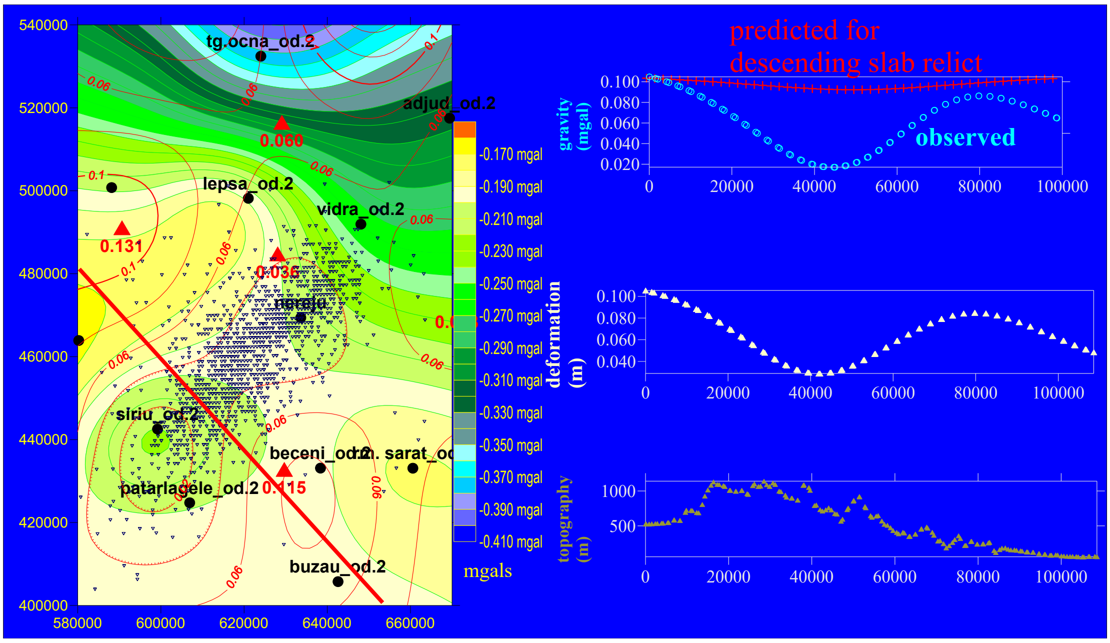

Figure 3.3.7. Non-tidal variation of gravity in the Vrancea area between 1980 and 2000 corrected for the effect of crustal deformation. Vertical crustal deformation by red contours; gravity in shades of colour. In black, VGDN stations; red triangles, GNSS stations (acc. Besutiu & Zlăgnean, 2008b).

Attempts for 2D numerical simulation of the mass deficit responsible for the gravity change started from the paleo-subduction scenario (where the sinking of the relic plate would leave behind a mass deficit), which could not justify the observed effect. Gravity change predicted by the model exhibits a wavelength much longer than the observed effect (Fig. 3.3.8).

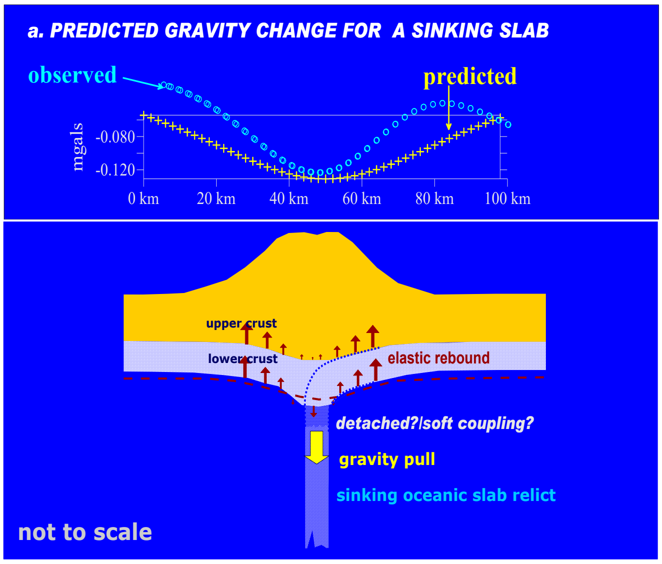

Fig. 3.3.8. Gravimetric effect of a sinking plate relic compared to the observed effect (after Besutiu *et al.*, 2008b).

To fit the predicted gravity to the observed effect, it was necessary to raise the top of the gravity source (the mass deficit) to a depth of about 10 km (Fig. 3.3.9). The new model seems to suggest a vertical deformation of the crust beneath the Carpathian Neogene overthrust. The thickness of Carpathian Alpine napes was estimated at 10–15 km by magnetotelluric soundings (Stănică *et al.*1986).

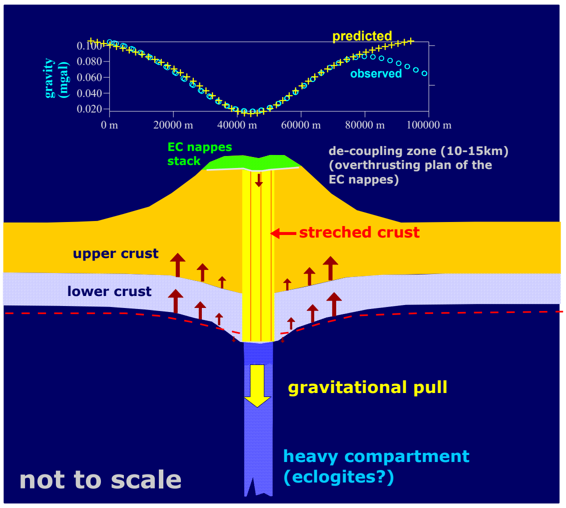

Fig. 3.3.9. Numerical simulation of the non-tidal gravity variation in Vrancea suggesting a vertical deformation of the crust below the Alpine overthrust of East Carpathian (after Besutiu *et al*., 2008b).

To monitor the evolution in time and space of the phenomenon, which seems to be related to internal geodynamic processes in the upper mantle, where intermediate Vrancea earthquakes occur, SEDD conducted systematic (usually annual) gravity surveys, with repeated determinations on VGDN benchmarks.

A problem during the monitoring was the integrity of the network benchmarks, which sometimes suffered irreparable damages that required relocation of the measuring sites and consequent fragmentation of the time series of observations (Fig. 3.3.10).

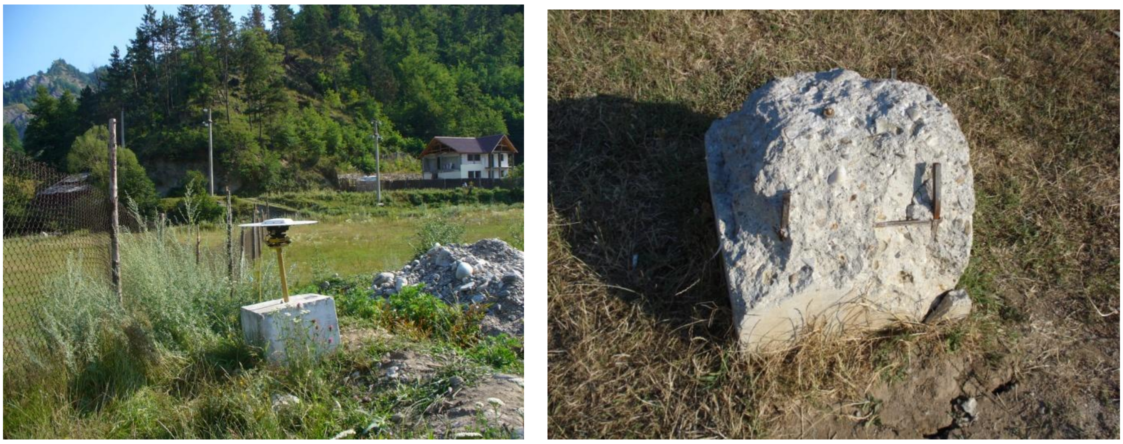

Fig. 3.3.10. Examples of destruction of network benchmarks.

Figure 3.3.11 presents a synoptic result of the monitoring of non-tidal gravity change between 2010 and 2018. Beyond the datum jumps due to the relocation of the measuring sites, the records seem to indicate permanent gravity lowering in the epicentre area, with a decreasing rate up to about10 μGal/year.

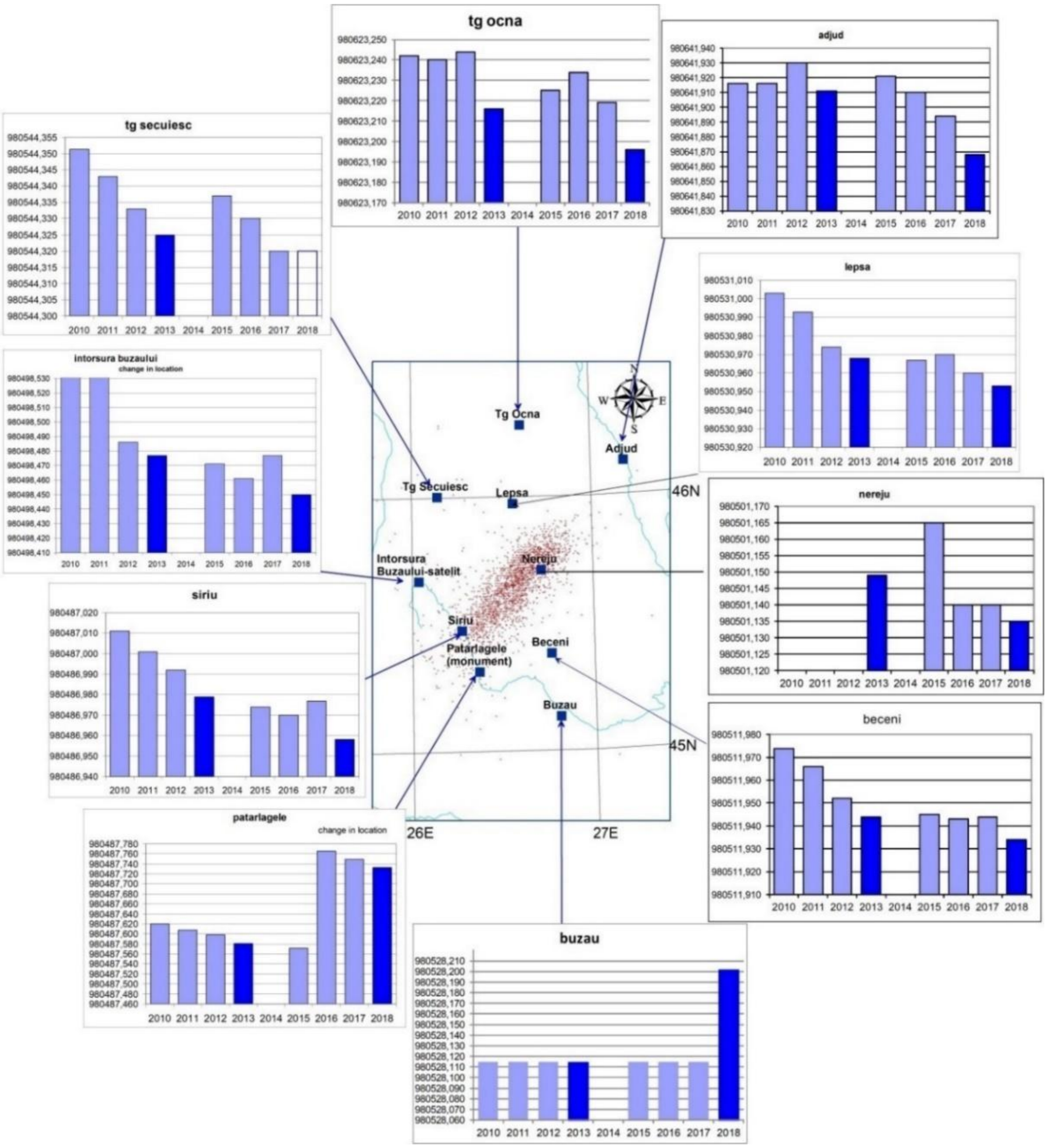

Fig. 3.3.11. Spatiotemporal evolution of gravity in the epicentres area of the Vrancea subcrustal earthquakes (after Besutiu & Zlăgnean, 2024b).

The continuous decrease in gravity suggests the existence of an active regional geodynamic process involving the lithosphere deformation and sinking.

The genesis of intermediate-depth earthquakes is probably associated with thermo-baric accommodation phenomena occurring into the lithospheric segment that penetrates the upper mantle (e.g., convection currents, thermal stress, or phase transforms accompanied by volume changes with expulsion of fluids from interstitial spaces).

3.3.2.4. Echoes of intermediate seismicity in the gravity field

The monitoring of the space-time gravity changes in the area of the East Carpathian bending zone unveiled an interesting relationship with the triggering of significant (M5+) intermediate-depth earthquakes.

Connections between earthquakes and gravity behaviour are known for a long time (e.g., Barnes, 1966; Hagiwara, 1977; Chen *et al*., 1979), and numerous studies are undertaken in this direction, especially in China.

In Romania, this research direction was introduced by the SEDD. During the gravity monitoring within VGDN, there were some cases when an intermediate-depth earthquake of higher magnitude occurred immediately after the annual network survey. In such a case, the gravity observations in the network were repeated. In this way, values of the gravity field were obtained both prior to and after the earthquake. Figures 3.3.12 and 3.3.13 present examples of the gravity change related to upper mantle events located at similar depths, but of different magnitudes (ML 5.5 / ML 5.8).

Following the analysis of the two cases, two main preliminary conclusions are to be mentioned:

(i) the gravity decrease over the earthquake epicentre area was unveiled *a posteriori*;

(ii) a direct correlation between the magnitude of the seismic event and the amplitude of the anomalous gravity signal seems to occur: the greater the amount of energy released, the higher the amplitude of the gravity change.

The problem is that the gravity observations were conducted only *before* and *after* the seismic event, and the question that persists is about *the moment of the gravity change*: before, coeval, or after the earthquake?

If the change occurred before the earthquake, then the next question would be *how long before* and whether this interval somehow *depends on the magnitude of the earthquake* that will follow.

The answer to these questions could pave the way for identifying and exploiting a precursory signal in the gravity field for significant earthquakes in Vrancea.

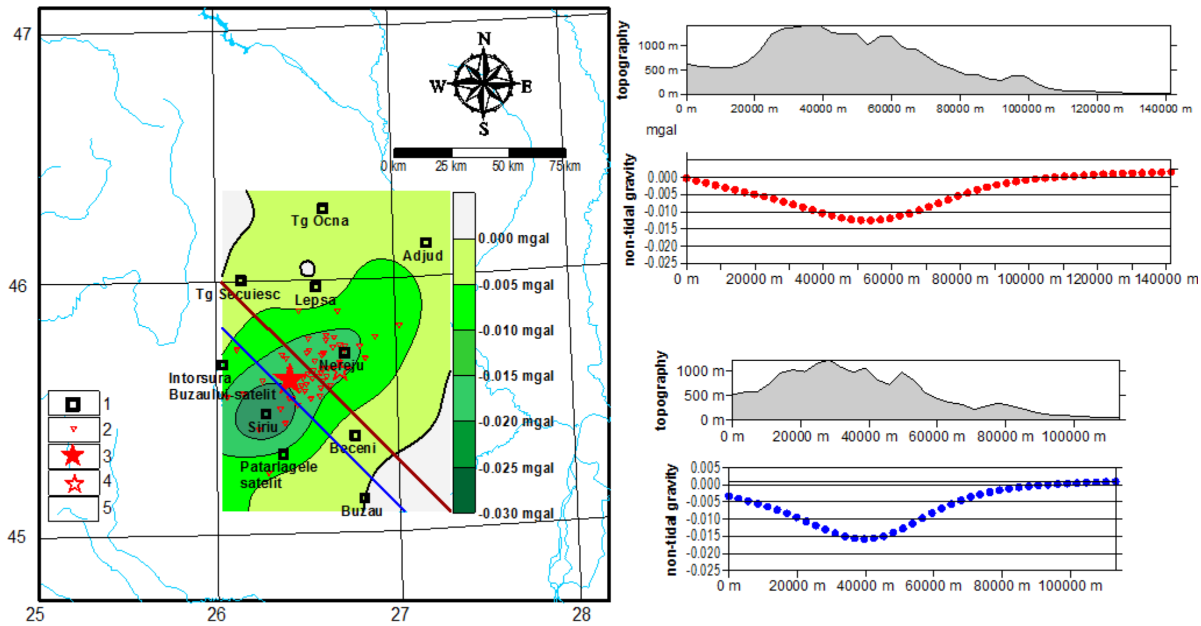

Fig. 3.3.12. Gravity variation during the ML5.5 earthquake (H=137 km) of October 6, 2013.
1, VGDN station; 2, earthquake epicentres that occurred between successive gravimetric campaigns before and after the event; 3, epicentre of the ML5.8 earthquake (H=148 km) of October 28, 2018; 4, epicentre of the ML5.5 earthquake (H=137 km) of October 6, 2013; 5, water stream (after Besutiu & Zlăgnean, 2024 b).

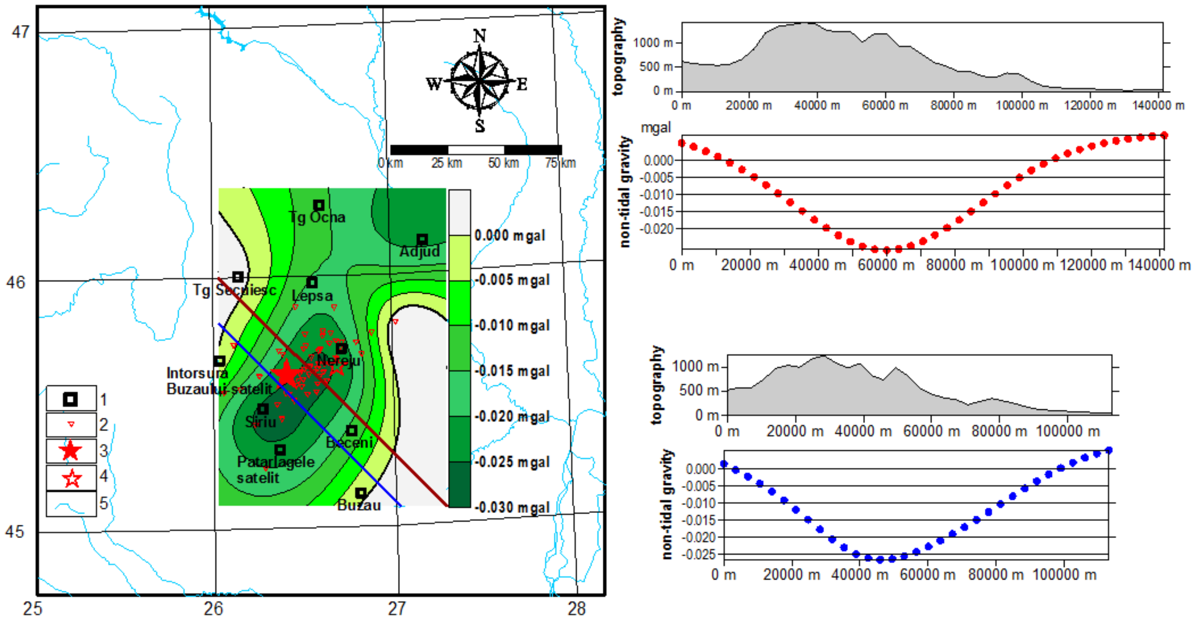

Fig. 3.3.13. Gravity variation during the ML5.8 earthquake (H=148 km) of October 28, 2018.
1, VGDN station; 2, earthquake epicentres that occurred between successive gravimetric campaigns before and after the event; 3, epicentre of the ML5.8 earthquake (H=148 km) of October 28, 2018; 4, epicentre of the ML5.5 earthquake (H=137 km) of October 6, 2013; 5, water stream (after Besutiu & Zlăgnean, 2024 b).

The fact that the gravity signal appears to be dependent on the magnitude of the earthquake gives it particularly valuable valences, suggesting the possibility of a selective potential warning, depending on the severity of the expected event.

A solution could be obtained through continuous recording of the evolution of gravity in an observatory located in the epicentre area; however, such an action would require special funding for the acquisition of adequate gravimetric and geodetic equipment.

3.4. GEOMAGNETIC INVESTIGATIONS

Research on the lithospheric geomagnetic field and its sources has encompassed a wide range of activities, from micro-magnetics survey to the construction of composite maps at national and international scales. Figure 3.4.1 illustrates, for example, the result of a micro-magnetic mapping of the BGO location area, aimed at identifying the PCF track (Besutiu *et al*., 2014).

The presence of the fault was identified as an apparent non-magnetic zone created by the random distribution of the direction of magnetization as a consequence of the mylonitization of rocks disposed along the contact, due to the friction between the fault-moving flanks (Fig. 3.4.2).

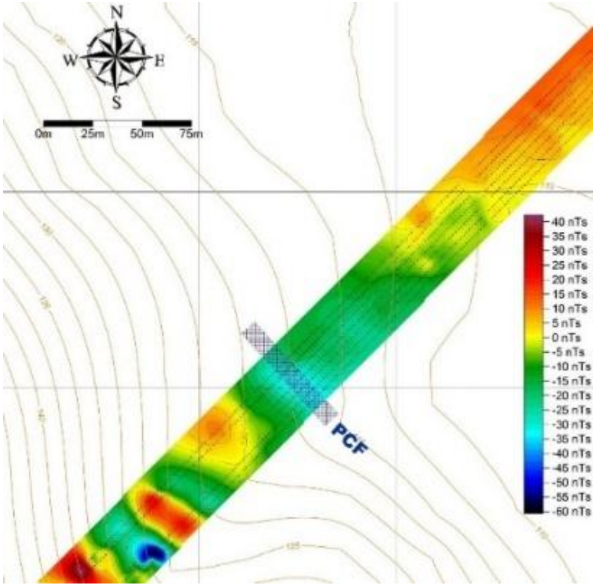

Fig. 3.4.1. Identification of the Peceneaga-Camena Fault trace in the BGO area, within a micro magnetism panel (after Besutiu *et al*., 2014).

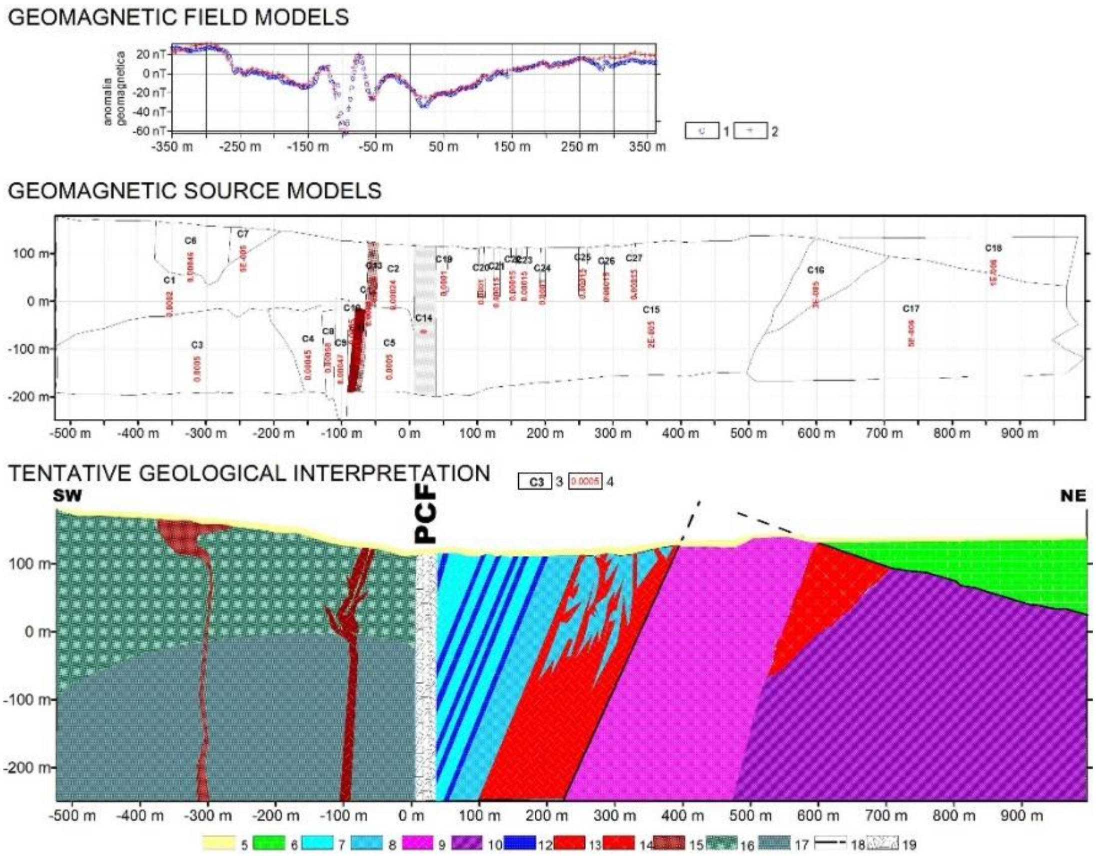

Fig. 3.4.2. Model based on the interpretation of magnetometric data along a profile crossing the PCF in the BGO area (after Besutiu *et al*., 2014).

Geomagnetic investigations were also carried out within the INSTEC project (Besutiu *et al.*, 2016a,b; Besutiu & Zlăgnean, 2017, 2018; Seghedi *et al.*, 2019; Besutiu *et al.*, 2023) to reveal the structures of Neogene-Quaternary volcanism within East Carpathians.

Figure 3.4.3 shows the geomagnetic anomaly in the central region of the Perşani Mountains and an interpretative section crossing the investigated area.

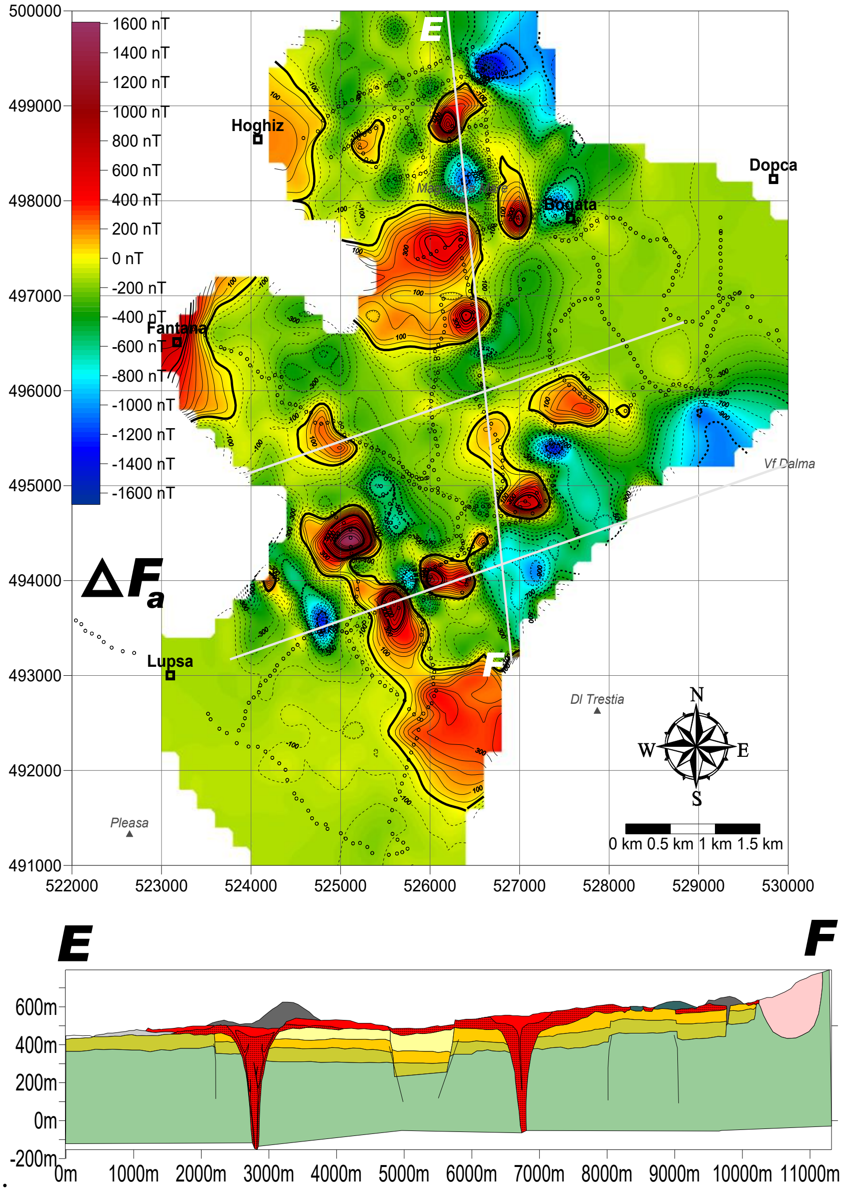

Fig. 3.4.3. Anomaly of the total intensity scalar of the geomagnetic field at ground level in the Perşani Mountains area (top) and attempt for interpretation of geomagnetic data (after Besutiu *et al.*, 2016 a).

The most significant SEDD achievement in the field of geomagnetism is undoubtedly the rehabilitation of the national aeromagnetic map within the framework of the DYGEF project (Besutiu *et al.*, 2008a). The project led by the SEDD included both fundamental research, related for example to the impact of the secular variation of the geomagnetic field upon the composite geomagnetic maps (based on different and long-lasting surveys over large territories), or the transfer of geomagnetic data from one surface to another, as well as experimental research related to the space-time consistency of previously obtained datasets, or the construction of a complex database, with an interactive access system (*Aidygef* application).

Finally, based on the homogeneous spatio-temporal data set, a geomagnetic field model was constructed for the entire territory of Romania (Fig. 3.4.4) and later integrated into the European and global context (Besutiu *et al.*, 2012).

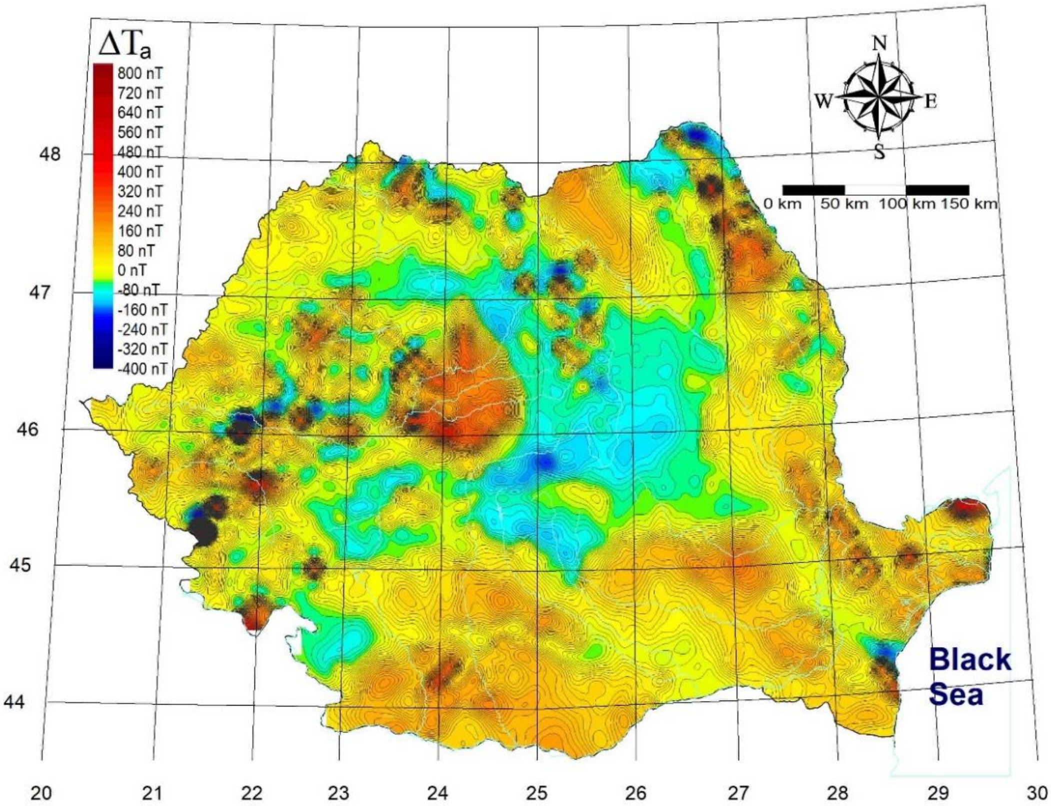

Fig. 3.4.4. Anomaly of the total intensity scalar of the geomagnetic field on the territory of Romania at 3000m above the Black Sea level (after Besutiu *et al.*, 2012).

The model enabled our country to participate in the international WDMAM (World Digital Aeromagnetic Anomaly Map) project, by contributing a 10 km × 10 km grid (Besutiu *et al.*, 2012; Lesur *et al.*, 2016). The first version of WDMAM (Korhonen *et al.*, 2007) had used data for the Romanian territory from the anomaly map of the vertical component of the ground geomagnetic field (Airinei *et al.*, 1985), significantly affected by effects of secular variation and by the use of an inadequate local reference geomagnetic field (Besutiu, 2009c).

Figures 3.4.5 and 3.4.6 illustrate attempts for the integration the national model with national models of the geomagnetic field in the Republic of Moldova, in collaboration with the Institute of Geophysics and Geology in Chisinau and Ukraine, in collaboration with the Institute of Geophysics in Kiev of the National Academy of Sciences of Ukraine (Besutiu *et al.*, 2005a; Besutiu *et al.*, 2006d).

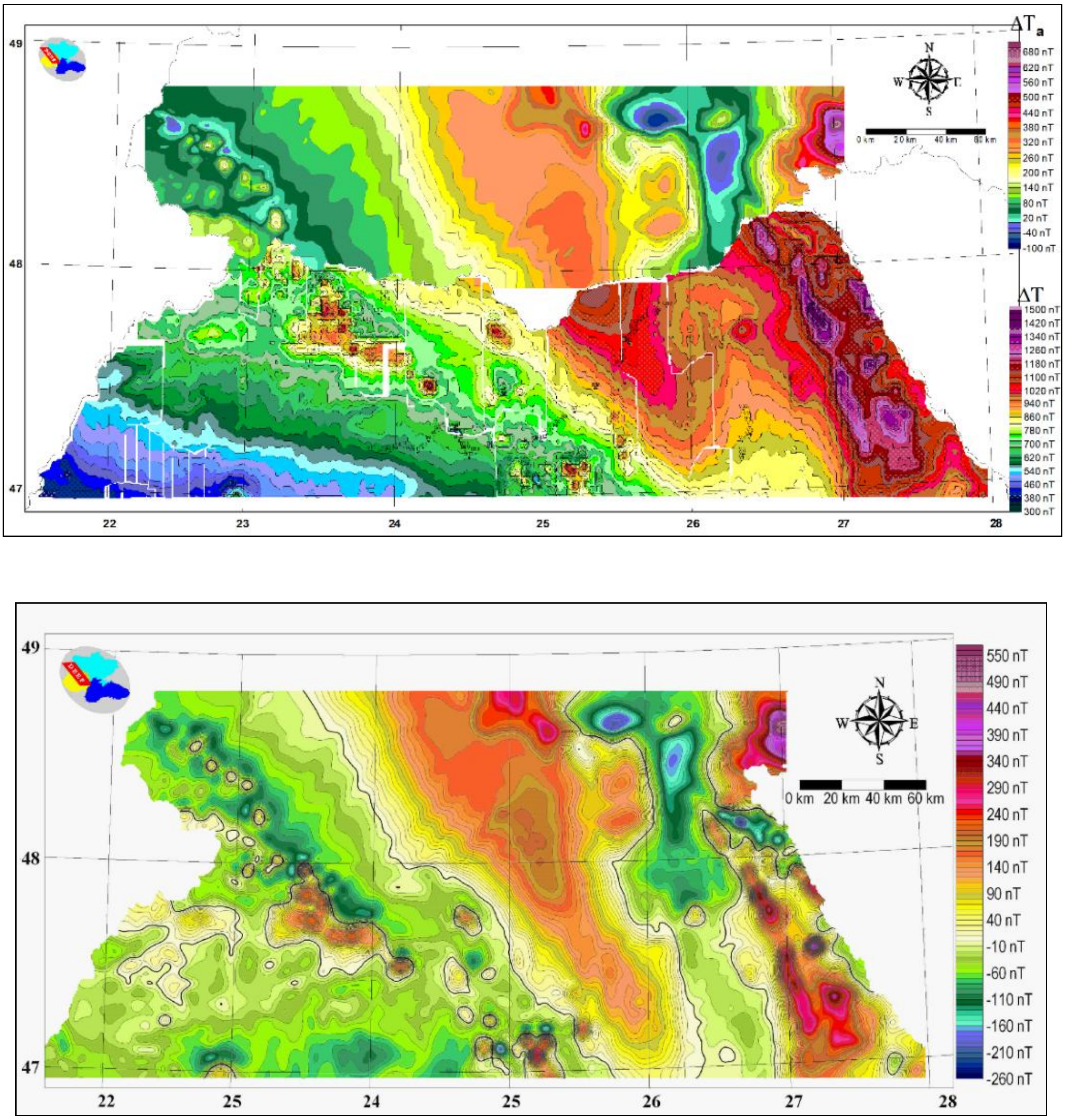

Fig. 3.4.5. Cross-border anomaly of the total intensity scalar of the geomagnetic field
in the area of the northern border of Romania with Ukraine before (top) and after the data homogenization
(Besutiu *et al*., 2012).

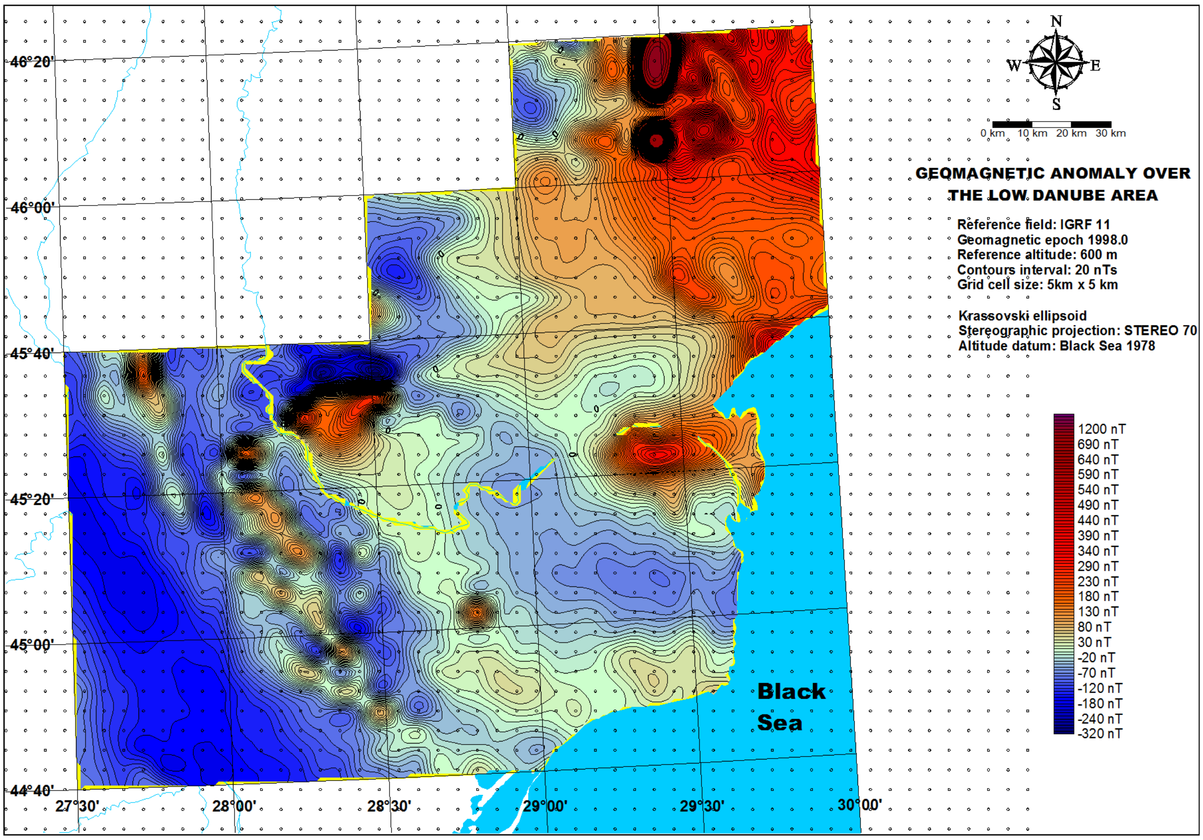

Fig. 3.4.6. Cross-border map of the total intensity scalar anomaly of the geomagnetic field in the Low Danube area, between Romania, the Republic of Moldova and Ukraine (Besutiu *et al*., 2015).

Large-scale geomagnetic images for the national territory were also derived from satellite data (Atanasiu, 2004; Atanasiu *et al*., 2005a).

Special mentions should be made to theoretical and experimental investigations carried out in the area of the Başpunar permanent geodynamics station, which made possible not only to outline the PCF track (needed for the correct placement of the total stations and associated reflectors), but also indirectly demonstrated the PCF active nature, by unveiling the existence of an electric current in the fault plane (Fig. 3.4.7). That was explained through the presence of electrolyte fluids and the permeability created by the mylonitization of the contact rocks due to the friction between the PCF flanks (Besutiu *et al*., 2014).

The conclusion of the research was based on the findings of a difference between day and night in the recordings of the two sensors of an SM-5 NAVMAG gradiometer (resolution 10^{-12} T) placed at different distances from the fault. The fact was attributed to the presence (during the day) or absence (during the night) of an electric current induced by ionospheric sources in the conductive zone separating the fault flanks (a consequence of the permeabilization created by the mylonitization produced by the friction of the flanks), the effect of which contributes to the observed geomagnetic field.

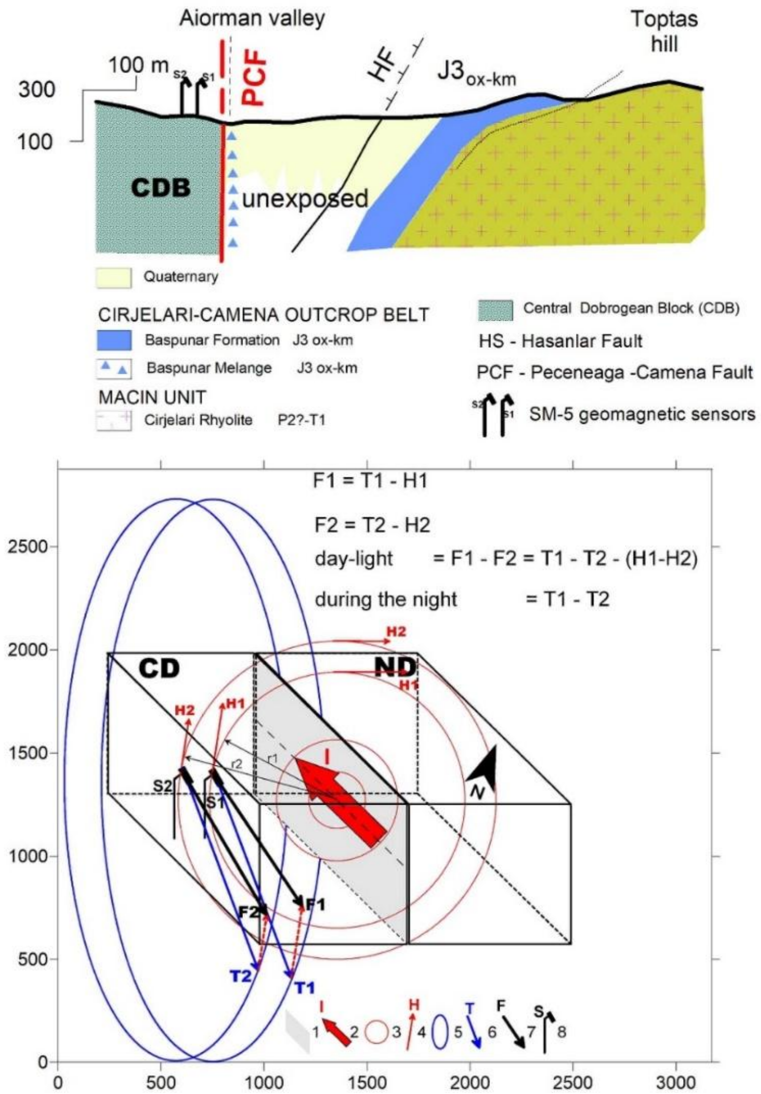

Fig. 3.4.7. Başpunar experiment: highlighting the existence of an electric current in the PCF plane (after Besutiu *et al*., 2014).

3.5. IMPLEMENTATION OF NUMERICAL SIMULATION FOR STUDYING THE STRUCTURE OF THE LITHOSPHERE

Numerical simulation of sources of the gravity and/or geomagnetic anomalies is a modern method of interpreting geophysical data, widely used in practice.

In principle, one can interpret data in two ways:

– interpretation using the solution offered by the direct problem (forward modelling)
– interpretation using solutions of indirect problem (inversion).

3.5.1. Numerical models based on forward modelling

The use of the direct problem in interpretation involves, in a first step, creation of a model of the underground structure (starting from current geological information), with a particular geometry of the compartments, to which the physical properties (density/ magnetization) obtained by laboratory or *in situ observations* are added. In the next step, the model predicted gravity/geomagnetic effect is computed and compared with the observations.

Adjustments to geometry and/or physical parameters follow, after which the gravity/geomagnetic effect is recalculated, and the comparison with the observational data is repeated. The process is interactive and may continue until the effect predicted by the model conveniently approaches the observed gravity/geomagnetic anomaly. It should be noted, however, that the solution obtained is not unique; the interpretation of potential fields offers an infinite number of solutions leading to the same effect. To reduce the degree of ambiguity, a series of constraints offered by observation methods independent of those that led to the acquisition of the modelled data (e.g., drilling or other geophysical works) are taken into account when defining the model. Constraints related to the geological reliability of the model play a decisive role in the acceptance of the solution.

The procedure is time-consuming, and requires solid multidisciplinary training of the interpreter. Therefore, for its implementation, automatic computing program packages have been developed, which can manage large volumes of data and perform complicated calculation operations within reasonable time intervals. SEDD employs the GMSYS 2D and 3D package, run under the OASIS platform (©GEOSOFT), for this purpose. This package enables for 2D or 3D simulation of potential field anomaly sources.

Figures 3.5.1–3.5.5 present some case studies.

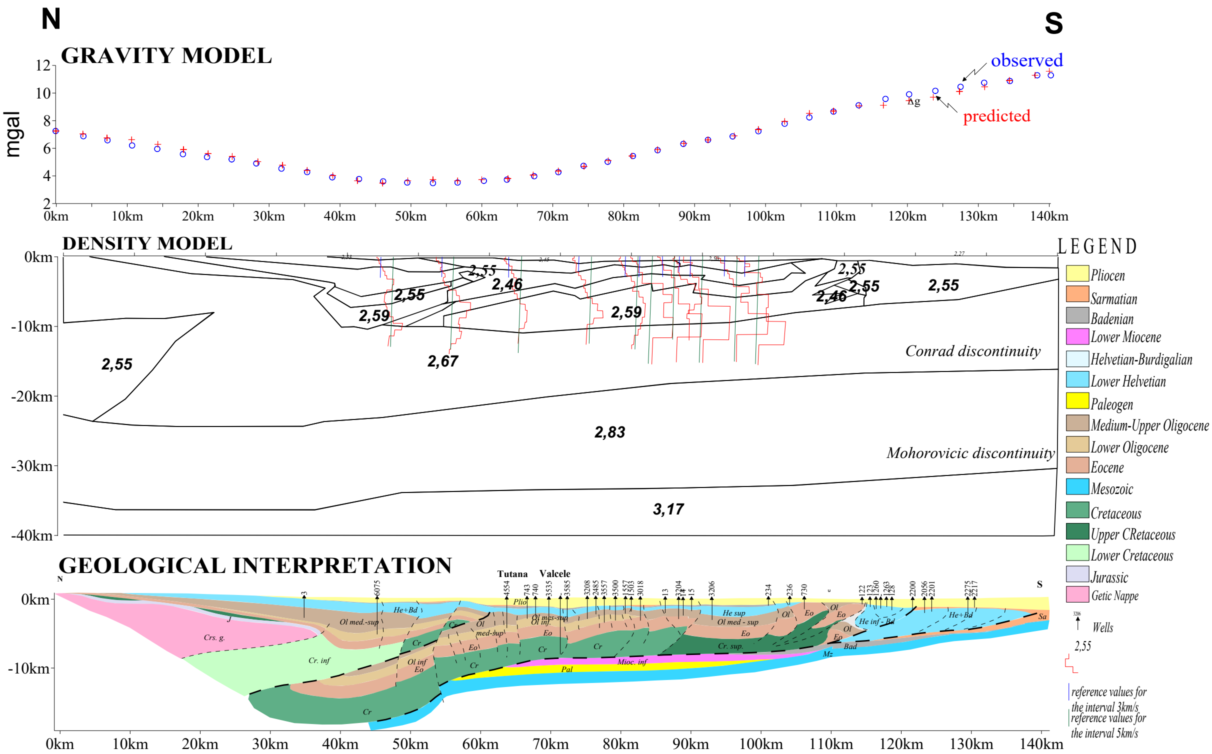

Figure 3.5.1. Interpretative solution of gravity data along a profile crossing the central area of the Southern Carpathians.

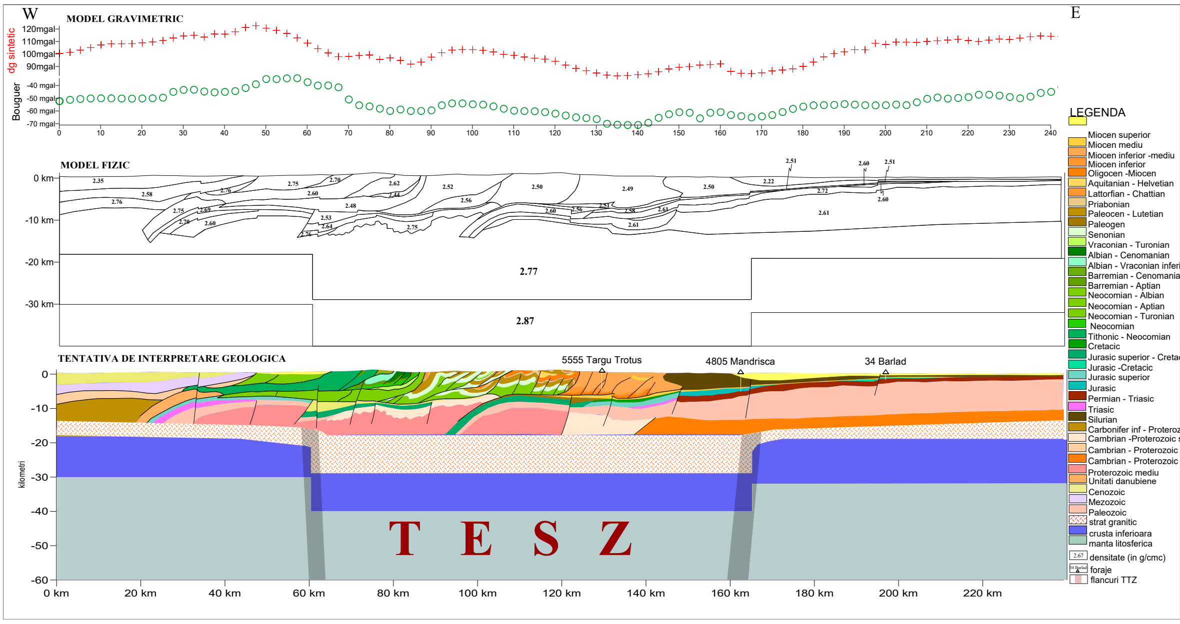

Figure 3.5.2. Interpretative solution of gravity data along a profile crossing the central area of the East Carpathians (INRAF project).

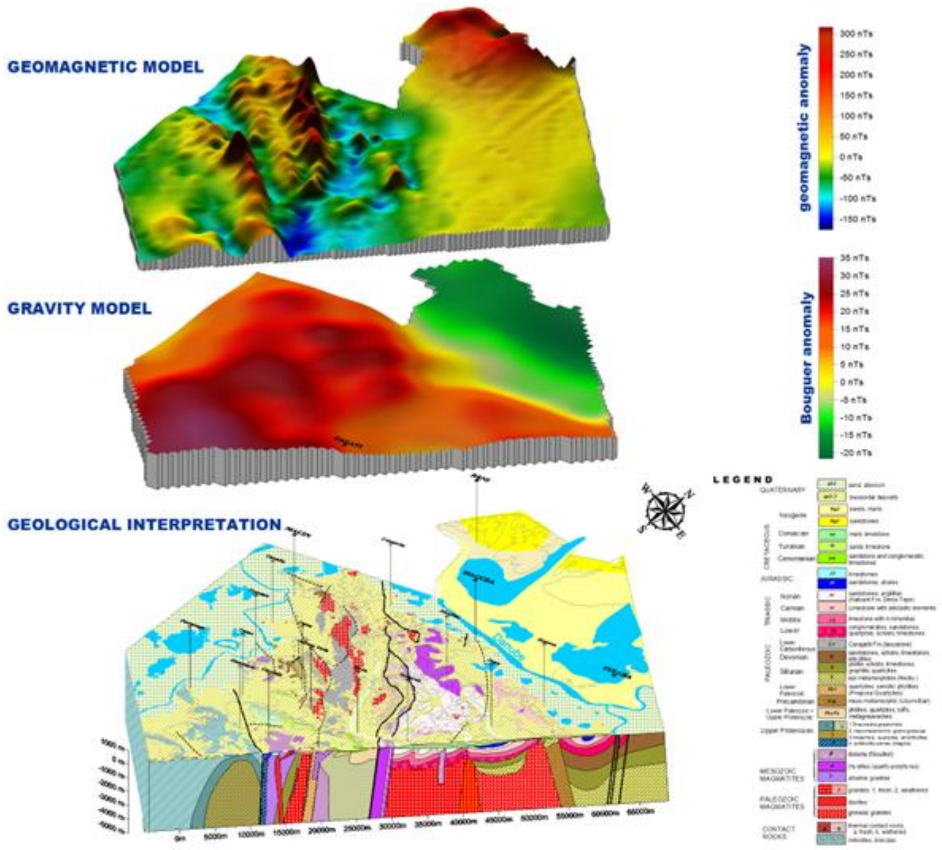

Figure 3.5.3. 3D geological model across the border in the Lower Danube area, built based on the interpretation of gravimetric and aeromagnetic data (Besutiu *et al.*, 2015).

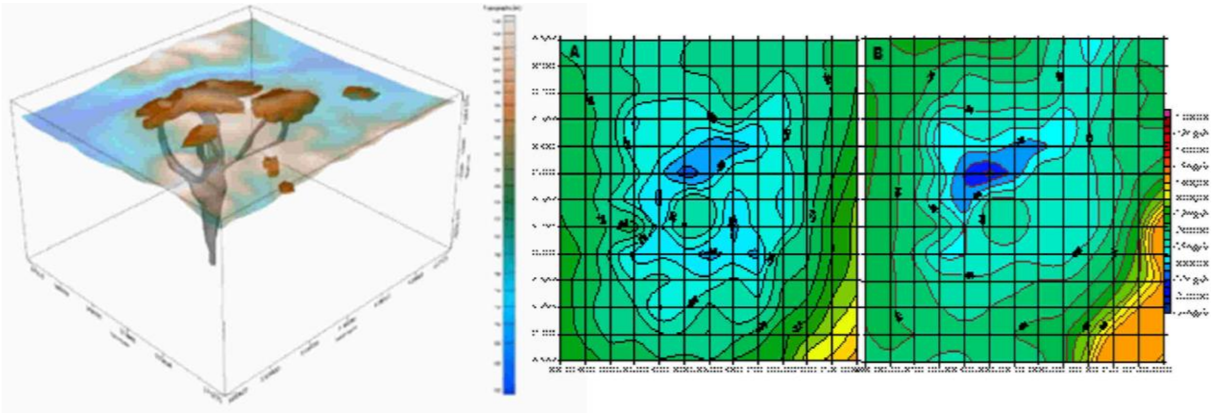

Figure 3.5.4. Model of the Ciomadu volcano plumbing system inferred from gravimetric data. A, Bouguer anomaly; B, the effect predicted by the model (Besutiu *et al*., 2021).

Figure 3.5.5 illustrates the results of the simulation of the mass deficit responsible for the gravity change over twenty years in the epicentres area of Vrancea intermediate earthquakes.

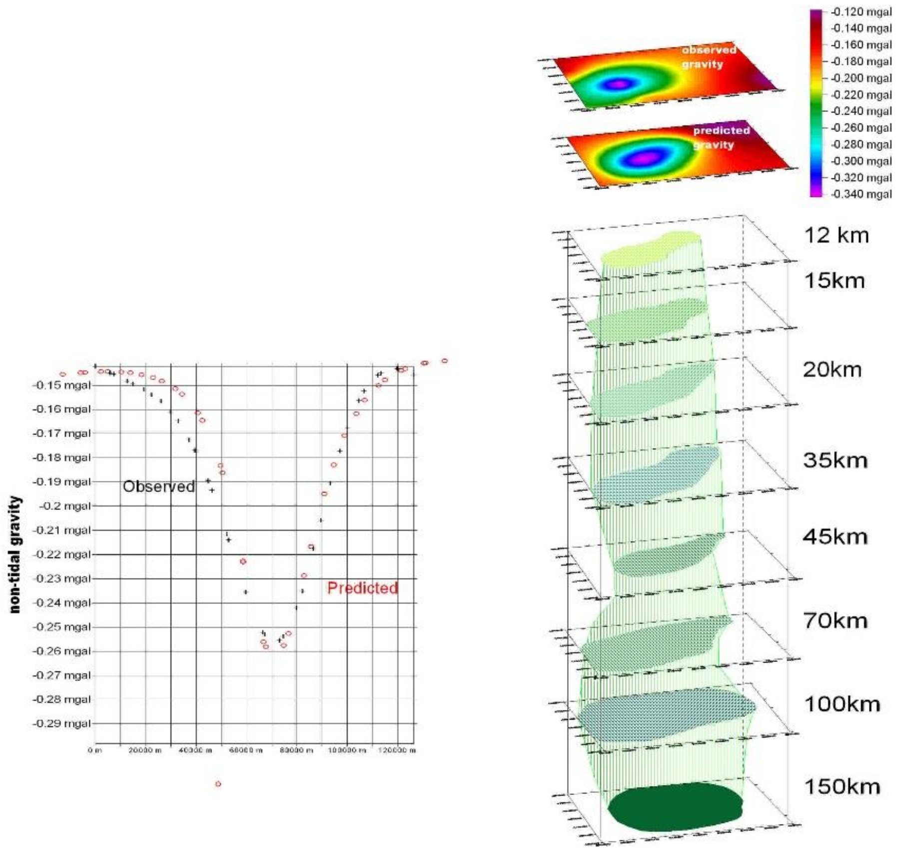

Fig. 3.5.5. Numerical simulation of the non-tidal variation of gravity in Vrancea (after Zlăgnean & Besutiu, 2008).

3.5.2. Inversion-based numerical models

In the case of the direct interpretation, source modelling is performed directly from observational data through inversion (e.g., Li & Oldenburg, 1998; Fullagar *et al*., 2000).

The acquisition of the OASIS package included the Geosoft VOXI Earth Modelling interface, which allows for the inversion of gravity and/or geomagnetic data.

Structural inversion of gravity data allowed, for example, the construction of a model of the top of pre-Neogene deposits for the region where the 2013 Galați–Izvoarele earthquake swarm occurred (Fig. 3.5.6).

Quality control was performed by comparing model results with data provided by a seismic survey line (the vertical section shown at the bottom of the figure, where filled circles represent gravity data, and empty circles seismic survey data). Small blue triangles on the map mark the epicentres of the earthquakes swarm.

Density inversion outlined the seismogene structure that generated the earthquake swarm, as a local graben on the descending slope of the North Dobrogea promontory, in front of the Pechea basement uplift (Fig. 3.5.7).

Details of this asymmetrical graben-like structure, with faulted flanks, are well outlined in a cross-section constructed based on the inversion of the geomagnetic anomaly in the area (Fig. 3.5.8).

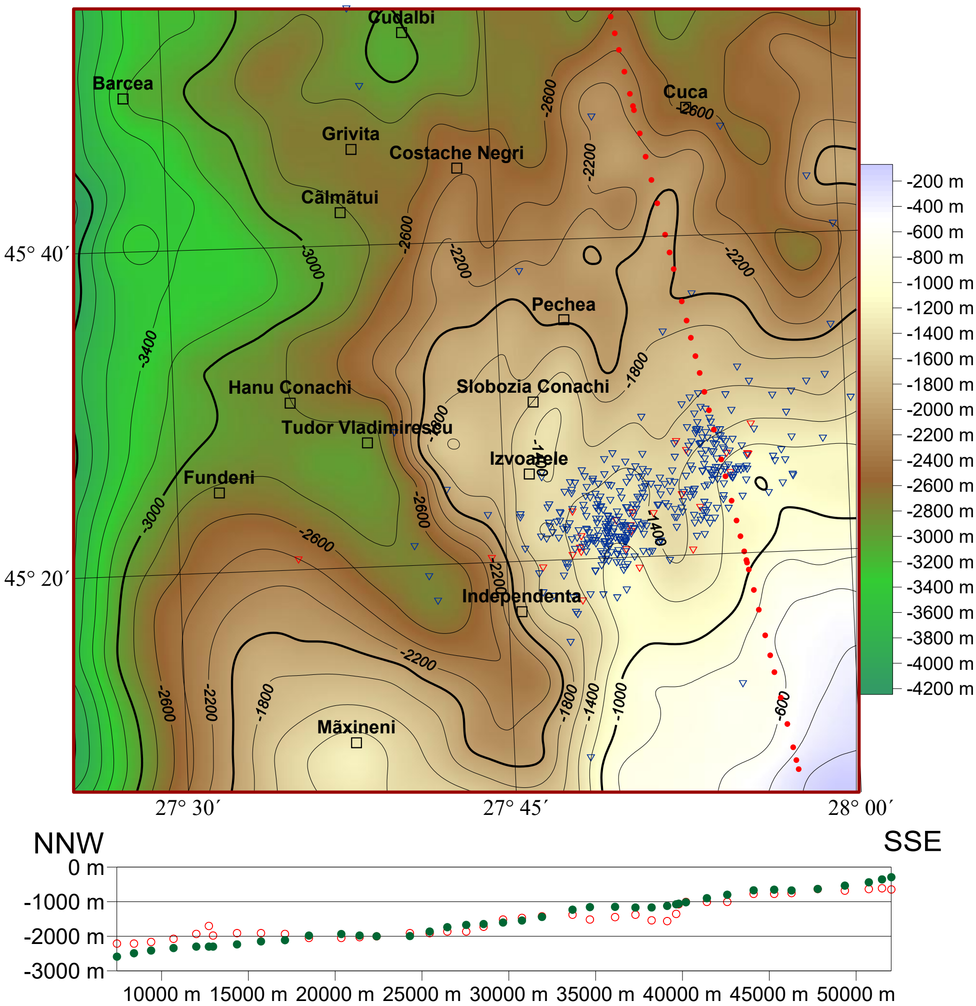

Figure 3.5.6. Surface of pre-Neogene formations from the active geodynamic area Galați–Izvoarele obtained by structural gravity inversion (after Besutiu *et al*., 2019).

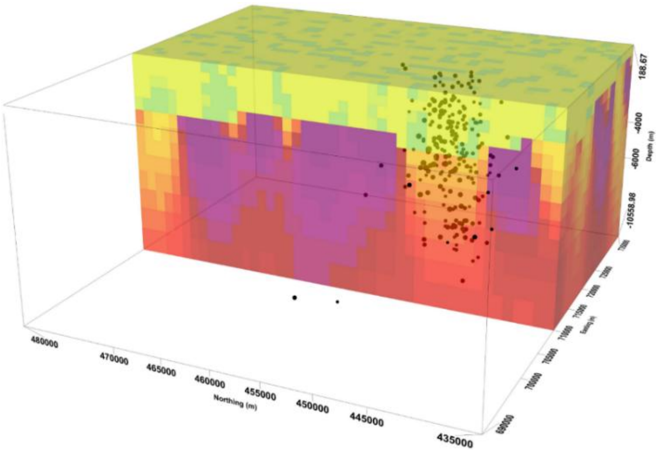

Figure 3.5.7. Seismogene graben-like structure that hosted the Galați-Izvoarele swarm, in a cross-section through the density voxel obtained by gravity inversion (after Besutiu *et al*., 2019).

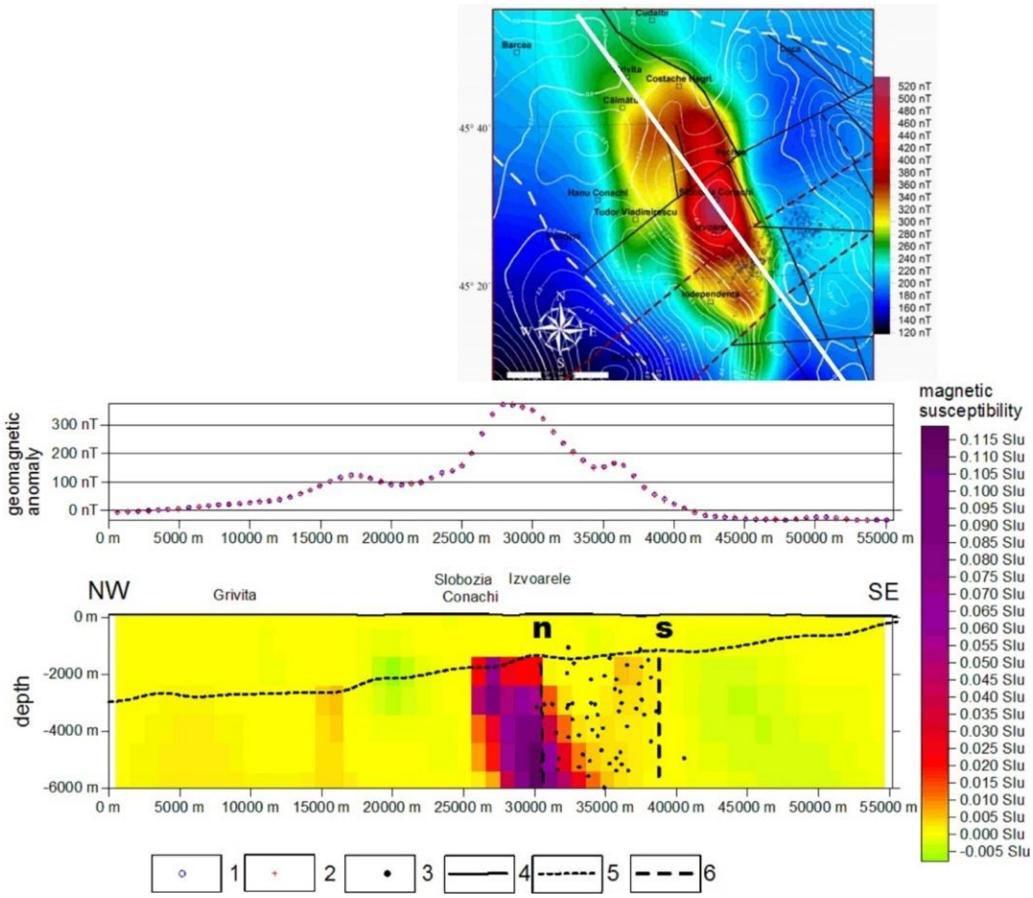

Figure 3.5.8. Observed and synthetic geomagnetic anomaly and detail of the graben that hosted the Galați–Izvoarele earthquake swarm in the architecture of the basement magnetic susceptibility obtained by inverting the scalar of the total intensity of the geomagnetic field (after Besutiu *et al*., 2019).

3.6. RESEARCH ADDRESSING TECTONIC SETTING OF ACTIVE GEODYNAMIC AREAS

3.6.1. Introduction

The presence of upper mantle seismicity in Vrancea, in the absence of active subduction and in a completely intracontinental environment, is a challenge for 21st-century researchers, despite decades of previous research.

Constantinescu *et al*. (1976) mentioned the presence of three major lithospheric compartments on the territory of our country that meet in the Vrancea area.

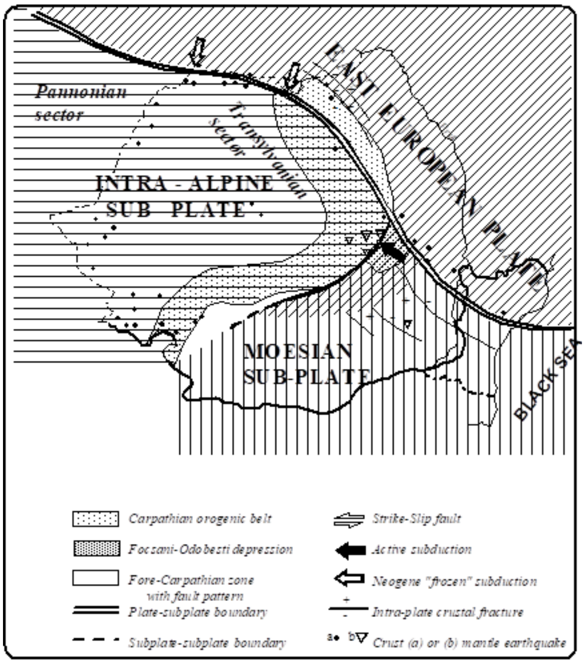

Figure 3.6.1. Sketch of the lithospheric compartments on the territory of Romania (after Constantinescu *et al*., 1976).

Deep magnetotelluric surveys (Stănică *et al*., 1986) have indicated a significant lateral variation in depth of the asthenosphere in the area, which seems to confirm the existence of different tectonic plates: 120–130 km for the MoP, 80–90 km for the IaP, and over 150 km in the case of the EEP. For the Vrancea area, magnetotelluric surveys have highlighted the asthenosphere at depths exceeding 200 km.

The track and nature of the contacts separating these compartments, i.e., the Trans-European Suture Zone (TESZ) between IaP and EEP, PCF between EEP and MoP, and TGF between MoP and IaP, were later on established, based on the interpretation of geophysical data (e.g., Besutiu, 2001a; 2003; Besutiu and Zlăgnean, 2006b).

3.6.2. Considerations on a possible Vrancea unstable triple junction

The model proposed by Constantinescu *et al*. (1976) was the first to suggest the existence of a triple lithospheric contact in the Vrancea area, and led to the idea of an unstable triple junction (e.g., Besutiu, 2001; Besutiu & Zlăgnean, 2006a).

A triple junction (McKenzie & Morgan, 1969; Turcotte & Schubert, 2001) is a complex contact where not two, but three tectonic plates meet (Fig. 3.6.2).

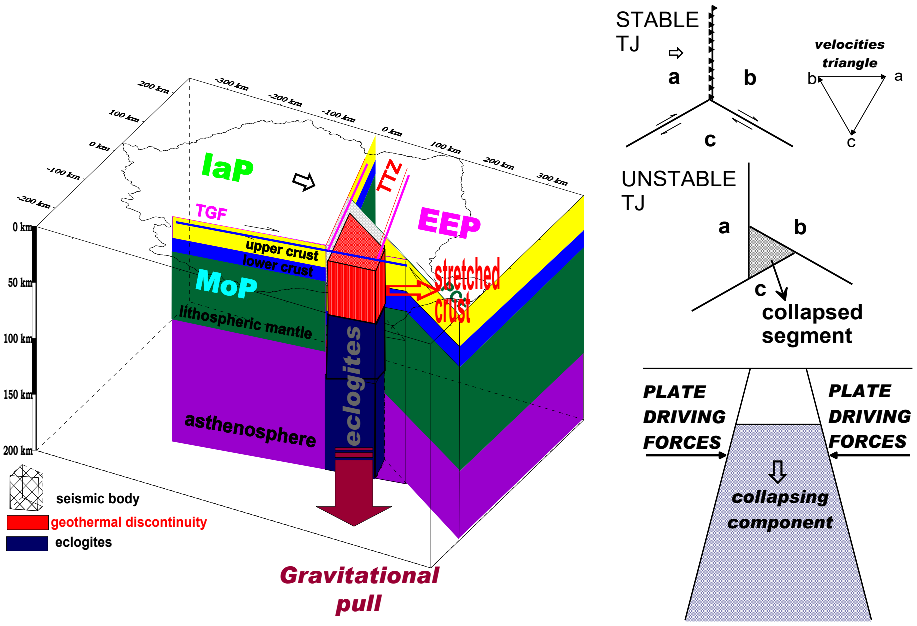

Figure 3.6.2. The principle of an unstable triple junction (compilation after Turcotte & Schubert, 2001) and the Vrancea unstable triple junction model (Besutiu, 2001 a).

When the three plates in contact have the same horizontal velocity, they move together, forming a stable triple junction (STABLE TJ in the figure). However, if, for some reason, one of them gains increased velocity, the equilibrium is broken, the plates slide relative to each other, and tectonic forces push the central segment of the lithosphere between them into the upper mantle due to an assumed reverse horst geometry (UNSTABLE TJ case).

Depending on the nature of the contacts between the three plates, several types of triple junctions are known (McKenzie & Morgan, 1969). In Vrancea, there appears to be a triple junction of the "transform-transform-compression" (TTC) type, the instability of which was likely triggered by acceleration of the MoP during the opening of the western Black Sea basin (Besutiu & Zugrăvescu, 2004).

High-resolution tomography, based on the integrated interpretation of seismological and gravimetric data (Tondi *et al.*, 2009), unveiled an in depth progressive increase of the horizontal cross-section of the central segment, suggesting geometric features typical for an unstable triple junction (Fig. 3.6.3).

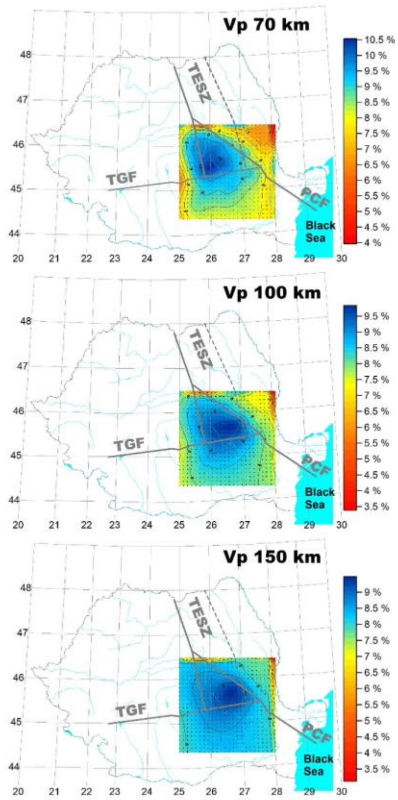

Figure 3.6.3. Vp tomography at various depths in the Vrancea area (based on Tondi *et al.*, 2009 data).

The penetration of the colder lithospheric compartment into the hotter upper mantle creates a thermo-baric disequilibrium and triggers accommodation phenomena that generate elastic waves. Convection currents shaking the sunken compartment, thermal stress, and volume change generated by phase transforms (e.g., albite passing into jadeite + quartz with a volume reduction of 17%, and further down, quartz transformed into coesit, with a further volume reduction of 16%) are important sources of seismicity. The minerals compaction induces implosions, but also explosions (due to the expulsion of fluids from the interstitial spaces of minerals) that generate seismic waves.

All these phenomena are more intense in zones of higher thermal contrast, i.e., at the contact with the asthenosphere of adjacent compartments.

The fact seems confirmed by the correlation between the frequency and the depth of earthquakes hypocentres (Fig. 3.6.4), which shows a maximum seismicity at the level of the asthenosphere of the three compartments in the contact (90–100 km for IaP, 120–130 km for MoP, and 140–150 km for EEP).

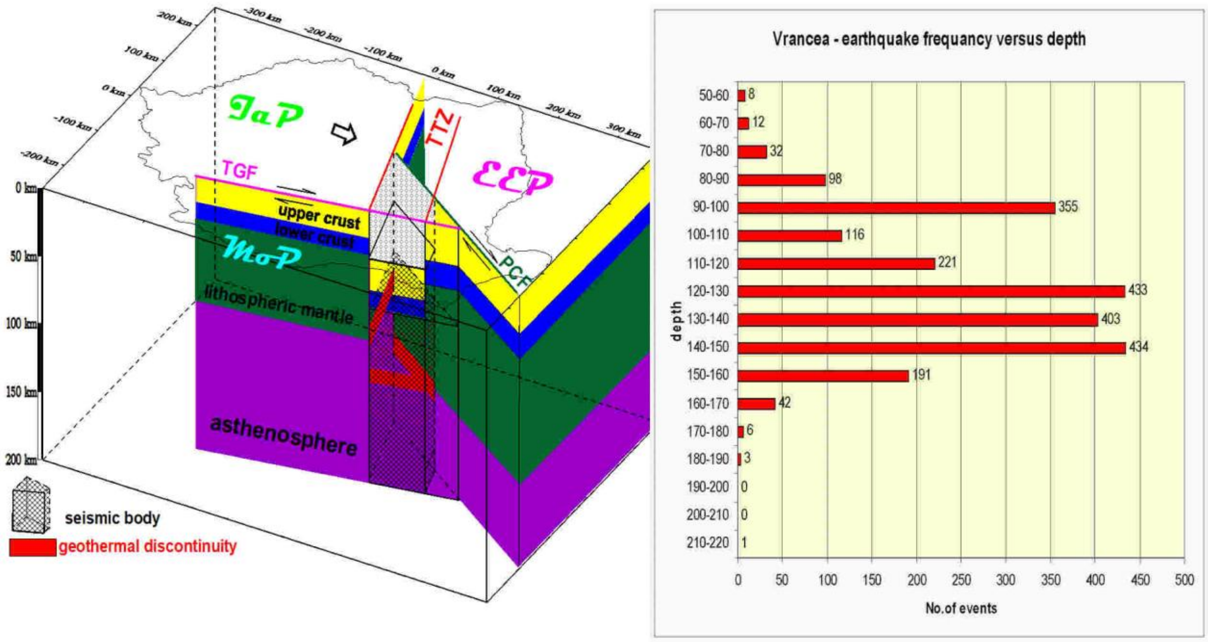

Fig. 3.6.4. Cartoon showing design of the Vrancea triple junction and the frequency of the in-depth distribution of hypocentres (Besutiu, 2009). The concentration of seismic activity is observed at the depths at which the asthenosphere is located in the adjacent compartments.

3.6.3. The impact of the opening of the western Black Sea basin on the inland

The opening of the Black Sea basin has a well-defined footprint in terms of residual geomagnetic and gravimetric anomalies (Fig. 3.6.5). Unlike the dominant E-V strike of the anomalies assumed in case of previous hypotheses, which assume the opening of the whole Black Sea basin in the N-S direction, as a back-arc extensional basin of northward subduction of the Neothetis Ocean floor (e.g. Nikishin *et al.*, 2001), the image shows residual anomalies of the both gravity and geomagnetic field with different strike, almost perpendicular each other for East and West Black Sea sectors. This suggests a distinct, consecutive opening of the West and East basins, in two each-other perpendicular directions (Besutiu, Zugrăvescu, 2004). In the W Black Sea basin, the correlation between the central gravity high and the geomagnetic high suggests a normal magnetic polarisation of an oceanic crust, likely during the Cretaceous calm period. Oppositely, within the E Black Sea basin, the gravity high (an echo of an oceanic crust) associates with the geomagnetic low, showing an opening in a later moment, of reverse polarization (Upper Cretaceous – Cenozoic?). The idea is supported by offshore seismic surveys for oil, which unveil the overthrust of East Pontide structures over West Pontide (Besutiu, Zugrăvescu, 2004).

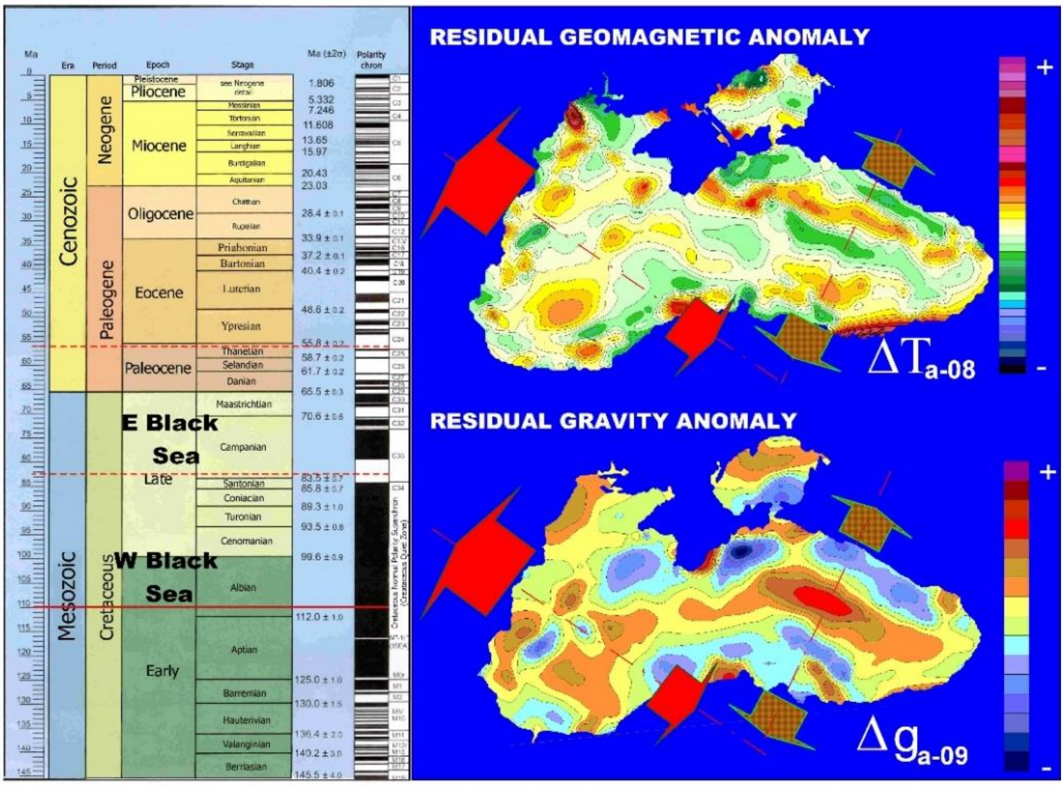

Figure 3.6.5. The opening of the Black Sea basin reflected by the residual gravity and geomagnetic anomalies. The arrows mark assumed directions of rift opening. On the magnetostratigraphic scale, the broken red lines mark the moments of the opening of the two basins (after Besutiu, Zugrăvescu, 2004).

The opening of the W Black Sea basin have had significant consequences for the eastern MoP (the so-called *Dobrogean sector*).

The lithosphere expelled by the rift split the Black Sea inland in front of Carpathians into a series of crustal/lithospheric compartments, creating or reactivating some major, NW-oriented faults, well outlined by P wave tomography (Martin *et al*., 2006), with well-known surface echoes like SGF, PCF, COF (Capidava-Ovidiu Fault), IMF (Intramoesian Fault), etc. (Fig. 3.6.6).

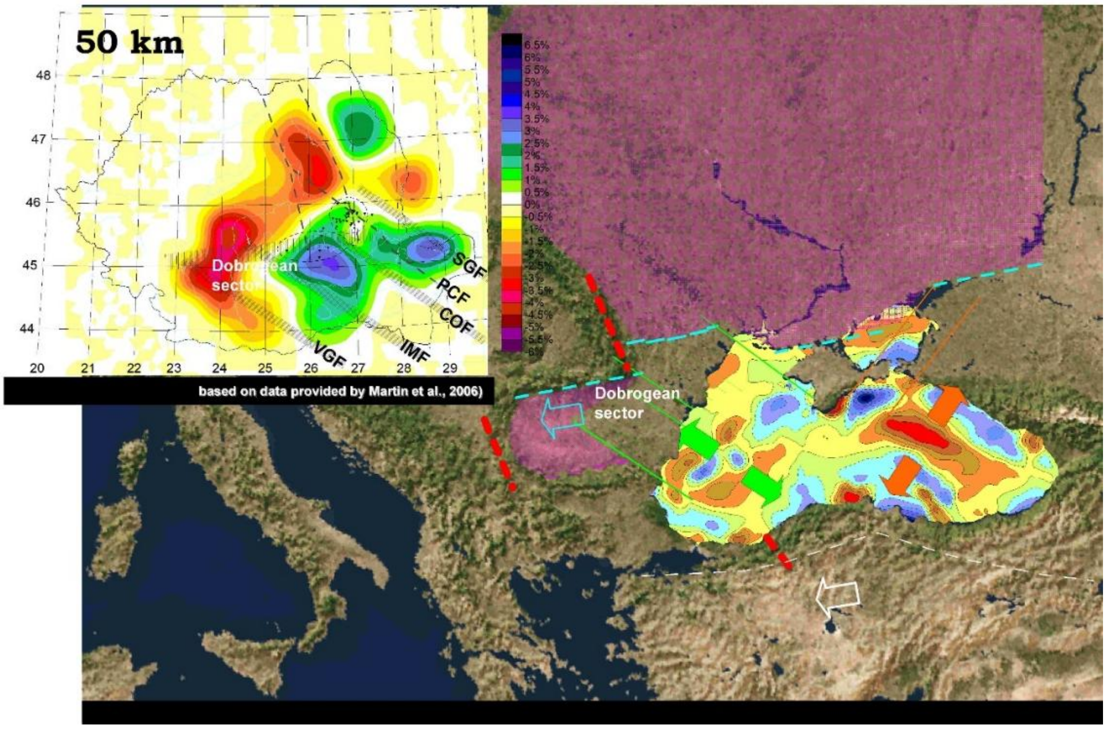

Figure 3.6.6. Gravity anomaly in the Black Sea basin, and MoP splitting under the lithosphere expelled by the opening of the W Black Sea basin (Besutiu, 2009). In the inset, the imprint of major faults in East MoP in P-wave tomography at the base of the crust (velocity data after Martin *et al*., 2006).

In addition, the Black Sea microplate push towards NW provoked the downward bending of the MoP in front of the quasi-vertical contact with the IaP, and consequent fissuring/fracturing of the platform along a system parallel to the mountain range (Fig. 3.6.7).

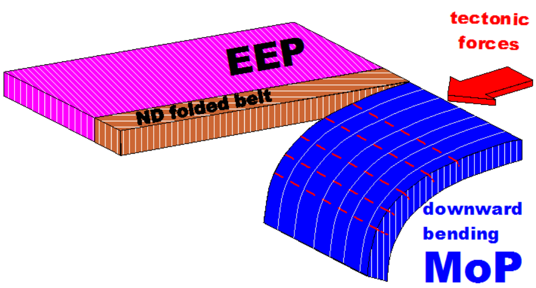

Figure 3.6.7. The mechanism of bending and longitudinal cracking/fracturing of the MoP in front of the TGF that led to the formation of the fault system parallel to the Carpathian chain.

Figure 3.6.8 provides a synoptic view of the surface echoes of the E MoP deep structures associated with the opening of the W Black Sea basin.

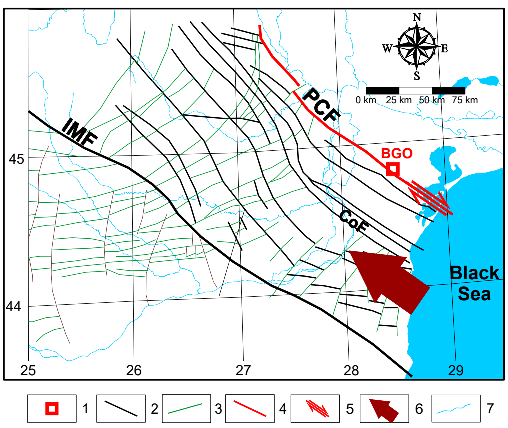

Figure 3.6.8. Tectonic sketch of the foreland of the East Carpathians Bend zone (modified after Visarion *et al*., 1988) 1, Başpunar Geodynamic Observatory; 2, faults created or reactivated by the lithosphere expelled by the W Black Sea rift; 3, faults generated by the MoP downward bending in front of the contact with IaP; 4, geodetic monitored fault; 5, dextral strike-slip dynamics; 6 tectonic stress generated by the Black Sea microplate; 7, water stream.

The sketch was constructed based on data provided by seismic surveys and oil wells (Visarion *et al*., 1988). The location of SEDD geodynamic observatory is also shown.

3.6.4. Considerations on the current geodynamic framework

After the end of rifting within the W Black Sea basin, the tectonic push towards the Carpathians continued due to the force exerted by the Black Sea microplate, indirectly driven by the active rifts in the Red Sea and the Aden Bay, which are currently moving northwards the Arabian Plate. The movement of the Arabian Plate is transmitted to the foreland of the East Carpathian bending zone through the microplates located between the African and Eurasian Megaplates (Fig. 3.6.9).

The thrust of the Black Sea microplate activates the fault systems in the Dobrogean sector of the platform, which triggers the unusual seismicity of the cratonic segment. It also determines the sinking of the central lithospheric compartment of the Vrancea unstable triple junction, accompanied by the occurrence of intermediate earthquakes (Fig. 3.6.10).

The intermediate seismicity should be generated within the volume of lithosphere pushed into thermo-baric disequilibrium, which amount depends on the speed of sinking into the upper mantle.

When Black Sea thrust is weak, the sink speed is slow, and limited volumes are gradually exposed to thermo-baric accommodation. Consequently, a small amount of seismic energy wold be released. Oppositely, a strong tectonic stress will determine a high-speed sinking, suddenly bringing large volumes of lithosphere into thermo-baric disequilibrium, which generates large amounts of seismicity. Such a process seems to have occurred during the March 4, 1977, Mw 7.4 disastrous earthquake, when seismic activity in Vrancea concentrated at an unusual depth (Besutiu, Cadicheanu, 2006).

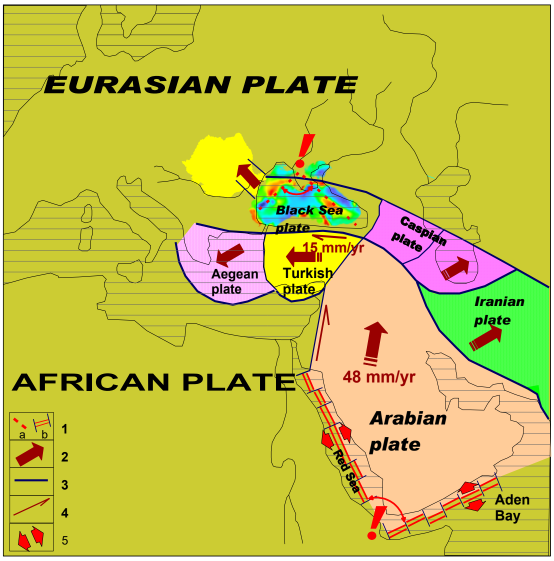

Fig. 3.6.9. Cartoon showing the geodynamic setting of the foreland of East Carpathians bending zone after the completion of the Black Sea opening (after Besutiu, 2001 a). 1, rift (a, paleo; b, active); 2, direction of movement; 3, strike-slip contact; 4, direction of rift expansion.

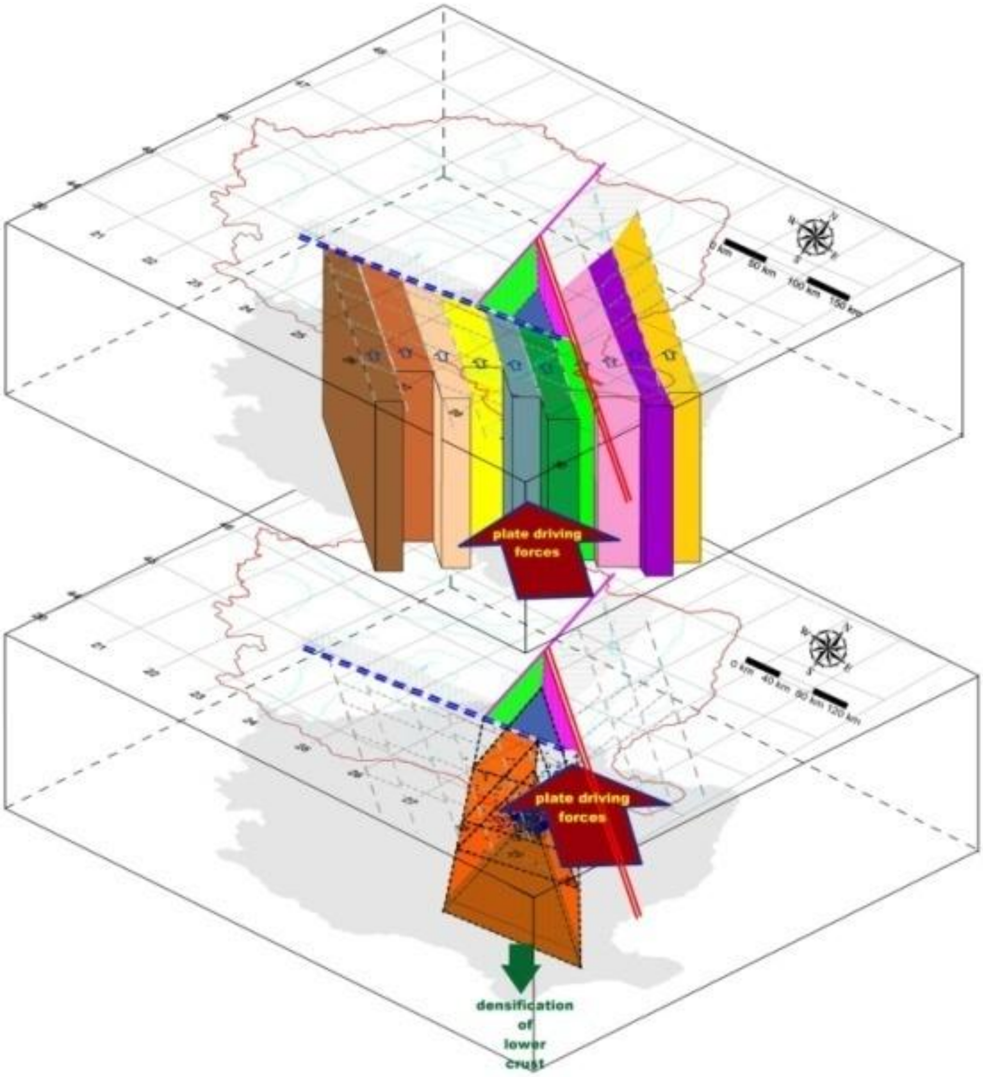

Figure 3.6.10. Cartoon showing seismogene structures in Vrancea and East MoP activated by the action of the Black Sea microplate (after Besutiu, 2009). Above: crustal earthquakes are triggered along edges of MOP compartments created by the Black Sea opening; below, intermediate earthquakes are induced by thermo-baric accommodation phenomena in the sunken lithosphere penetrating the upper mantle of the Vrancea zone.

To explain the unusual crust seismicity of the eastern part of the Moesian craton, Besutiu (2001b) has addressed the above-mentioned geodynamic model.

By using polynomial regression, the epicentres of main crustal earthquakes were clustered along the well-known faults that split the platform (Fig. 3.6.11).

Different colours were used to mark events triggered along different faults, and the size of the symbol representing the epicentre is proportional to the magnitude of the respective earthquake.

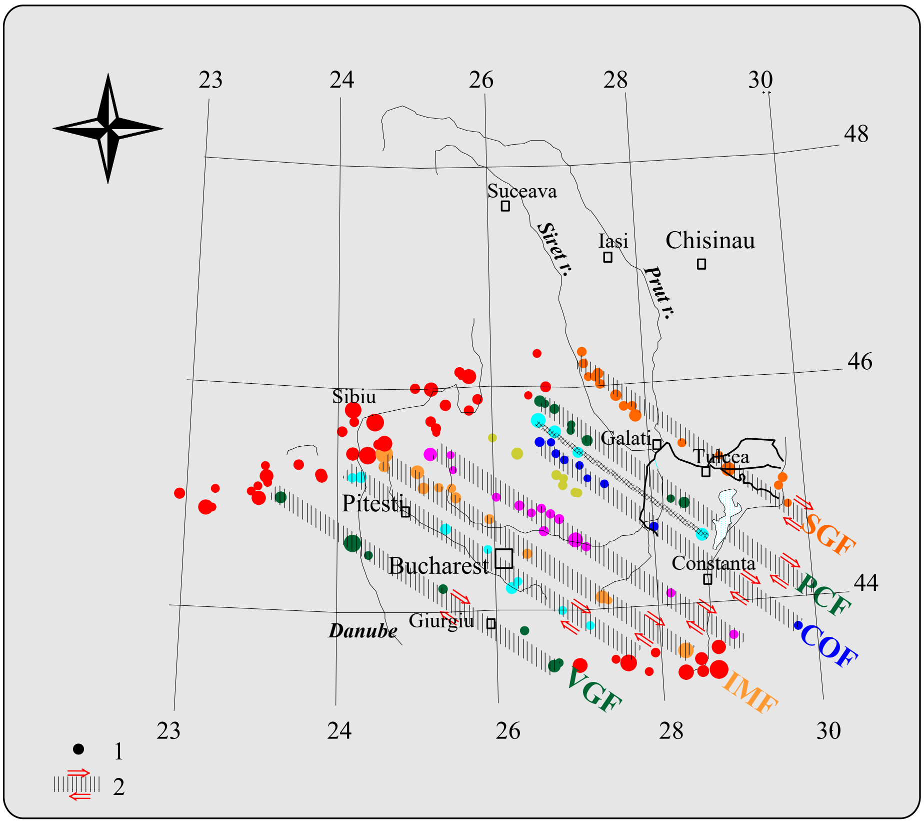

Figure 3.6.11. Alignment of crustal earthquake epicentres in the Dobrogea sector of the Moesian craton along the fault systems created or reactivated by the opening of the western Black Sea basin: SGF, PCF, COF, IMF, VGF (Varna Giurgiu Fault). 1, epicentre; 2, fault zone (after Besutiu, 2001b).

3.7. NUMERICAL SIMULATION OF THERMODYNAMIC PROCESSES IN THE UPPER MANTLE

3.7.1. Introductory

The numerical simulation of thermodynamic processes in the upper mantle is a recent research direction within the SEDD. It represents a first step in implementing a modern discipline for investigating the composition and dynamics of the Earth: numerical geodynamics.

The activity started with the creation of the high-speed supercomputer within the CYBERDYN project, the first parallel computing system in the field of geosciences built in Romania.

The SEDD team carried out the project under the direct guidance of Professor Vlad Constantin Manea from the National Autonomous University of Mexico, who thus laid the foundations of numerical geodynamics in our country (e.g., Manea *et al*., 2012a, b).

Basically, modelling the upper mantle involves a rigorous mathematical approach, where the analysed domain is discretized into a network of elementary compartments that are spatially confined enough for considering the uniform behaviour within them (Fig. 3.7.1).

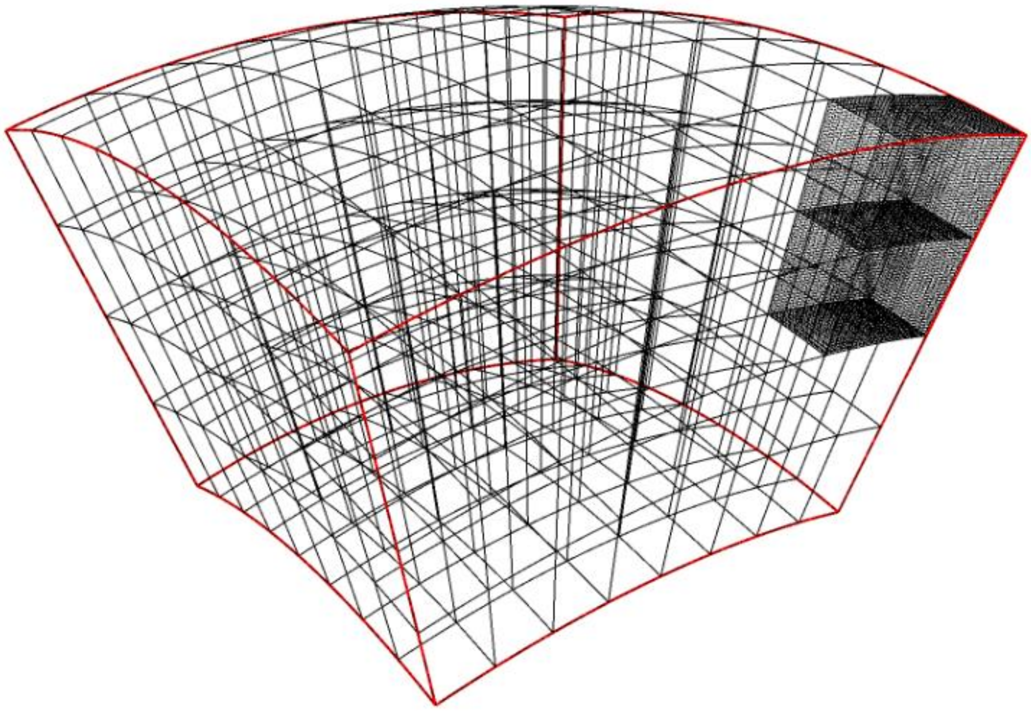

Figure 3.7.1. Clustering the computing space for employing the finite element theory.

Typically, to save computational effort, these networks are designed with a variable pitch, choosing distinct densities depending on the area of interest.

The next step is to write and solve a system of equations that describes the conditions of thermodynamic evolution in each of the above-mentioned elementary homogeneous compartments/ elements.

The basic equations are:

a) continuity equations (in Euler form) describing the evolution of the density (ρ):

$$\frac{\partial \rho}{\partial t} = div(\rho_v^\rho) = 0$$

b) Navier – Stokes equations, which describe the state of stress (σ):

$$\frac{\partial \sigma'_{ij}}{\partial x_j} - \frac{\partial P}{\partial x_i} + \rho g_i = 0$$

c) heat conservation equations:

$$\rho C_P \left(\frac{\partial T}{\partial t} + \vec{v}\nabla T\right) = \frac{-\partial q_i}{\partial x_i} + H$$

The three equations should apply to each node of the network, which generates an enormous system of equations. For example, the computational space considered for the numerical simulation of the impact of a thermal anomaly with a triple lithospheric contact (Besutiu *et al.*, 2017) required a computational network consisting of 8,388,608 nodes.

Normalizing and solving a system of 3 × 8,388,608 equations obviously required a computational effort that would not have been possible without the use of a parallel computing system.

3.7.2. Numerical simulation of various geodynamic scenarios for Vrancea zone

Over time, scientists have suggested various models for the evolution of the East Carpathian bending area in the attempt to explain the unusual upper mantle seismicity of the Vrancea zone. The most widespread seems to be the idea of a paleo-subduction followed by continental collision and slab break-off (e.g., Sperner *et al.*, 2001, 2004).

Figure 3.7.2 illustrates the results of the numerical simulation of such a process. The simulation was carried out within the CYBERDYN project, running on the SEDD cluster.

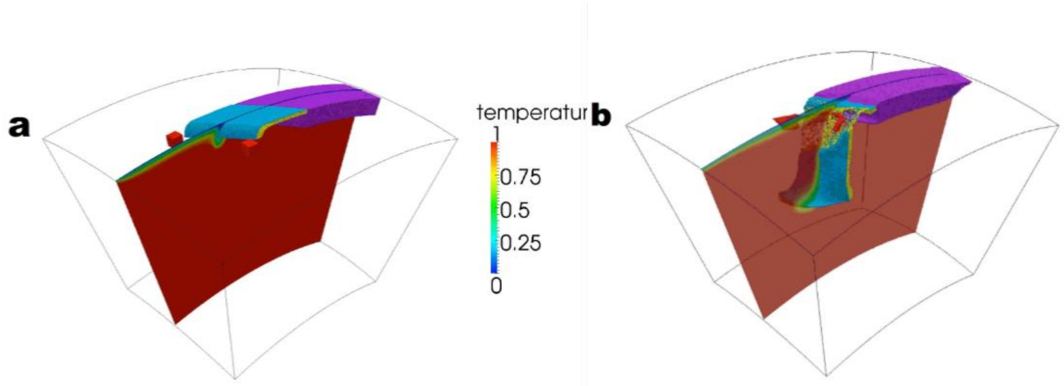

Figure 3.7.2. Numerical simulation of a continental collision scenario followed by weak break-off: a, at the initial moment; b, after 40 Ma (Manea *et al*., 2013).

Since subduction-based models fail to explain some aspects (such as the absence of associated volcanism), other geodynamic scenarios related to the genesis of intermediate-depth seismicity within the Vrancea zone have been imagined, including some unconventional ones such as the Rayleigh-Taylor gravitational instability (Lörinczi & Houseman, 2009) or the unstable triple junction (Besutiu, 2001a).

Fig. 3.7.3 presents a numerical simulation of a gravitational instability process. A vertical deformation of the lithosphere that sinks into the upper mantle is clearly unveiled.

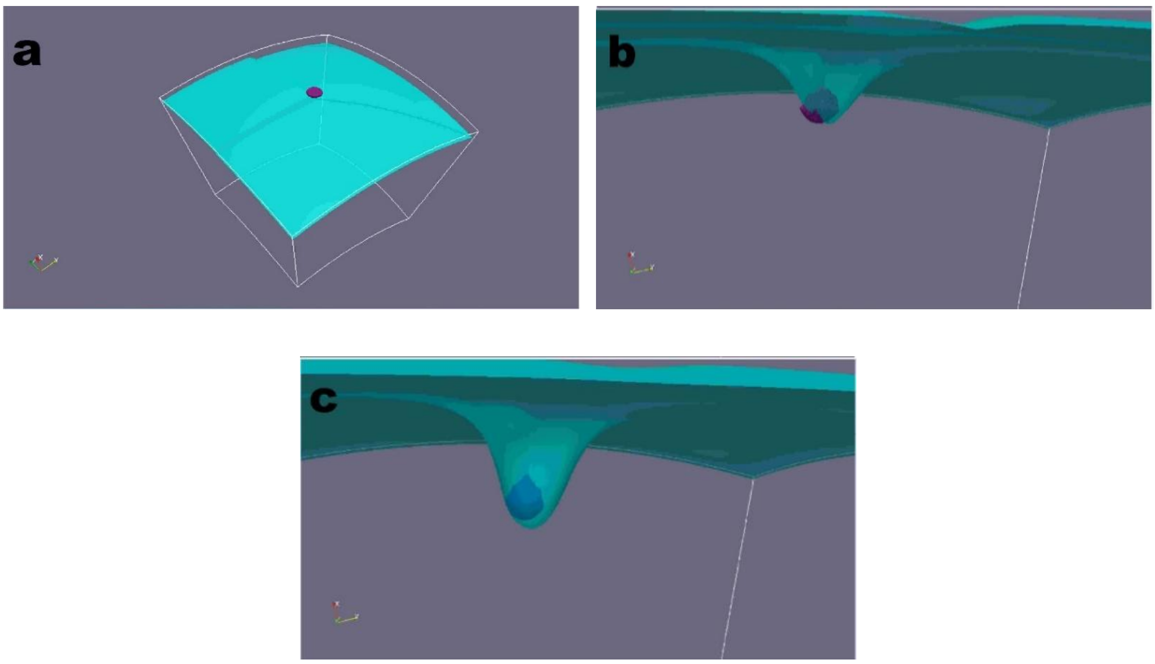

Figure 3.7.3. Numerical simulation of the Rayleigh-Taylor gravitational instability process: a, initial stage (the dark red disk represents a segment of eclogitized lithosphere); b, after 13.5 Ma; c, after 20 Ma (after Manea *et al*., 2013).

3.7.3. Evolution of a triple lithospheric contact under the impact with a thermal anomaly

The scenario was inspired by the presence of three lithospheric compartments with different thicknesses in the Vrancea zone, where intermediate seismicity is observed. One geodynamic scenario that attempts to explain genesis of intermediate earthquakes assumes the existence of an unstable triple junction in the area (Besutiu, 2001a).

The genesis of such structures is not fully elucidated. Basic idea is that instability occurs when the three plates in contact have–different velocities (Turcotte & Schubert, 2001). However, the hypothesis is speculative, not rigorously demonstrated. Therefore, taking advantage of the possibilities offered by the available HPCC, the SEDD attempted a numerical simulation of the evolution of the triple lithospheric contact in Vrancea under heating of the lithosphere bottom during the opening of the Black Sea basin (Besutiu, 2001a; Besutiu & Zugrăvescu, 2004).

It has been assumed that the geothermal anomaly in the mantle was generated into the upper core the thermo-chemical accommodation convection currents (Besutiu *et al*., 2017).

The temperature of 1340°C was considered the base of the lithosphere and the temperature contrast of the thermal anomaly was +380°C. The radius of thermal anomaly was 300 km (sufficient to affect both the rifting area of the W Black Sea basin and the Vrancea zone). The thicknesses of the plates in contact are 90 km, 150 km, and 190 km, figures coherent with geophysics provided data. The main limitation of the model is the assumption of the same viscosity within all compartments in contact.

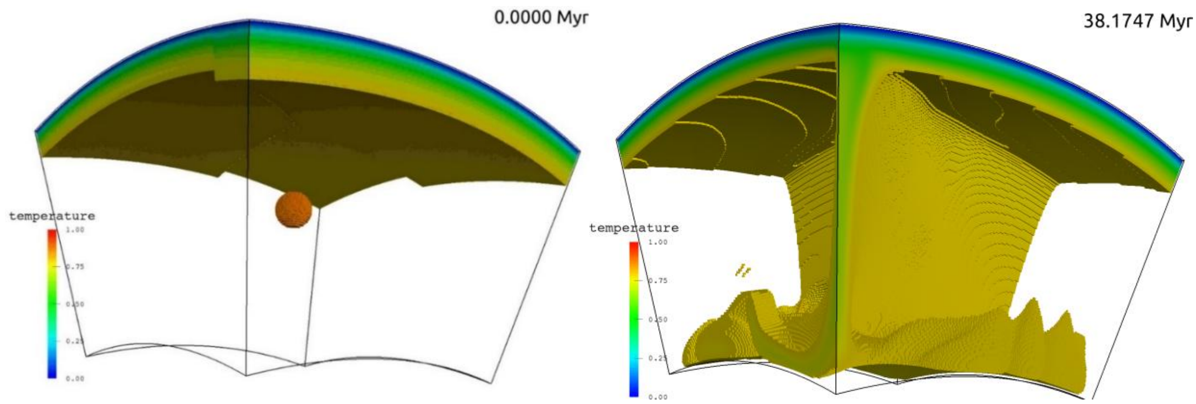

Figure 3.7.4. Triple lithospheric contact prior to, and 38 Ma after the impact with a thermal anomaly (Besutiu *et al*., 2017).

Two evolutions were analysed: (a) in the presence, and (b) in the absence of the impact of the geothermal anomaly.

It should be stressed that for both cases, a zero relative velocity between the three contact compartments was considered.

Whether in the absence of heating, the triple junction proved stable, in case of the thermal impact, it became unstable after approximately 38 Ma, adopting a surface geometry similar to the current situation in the Vrancea area (Fig. 3.7.5).

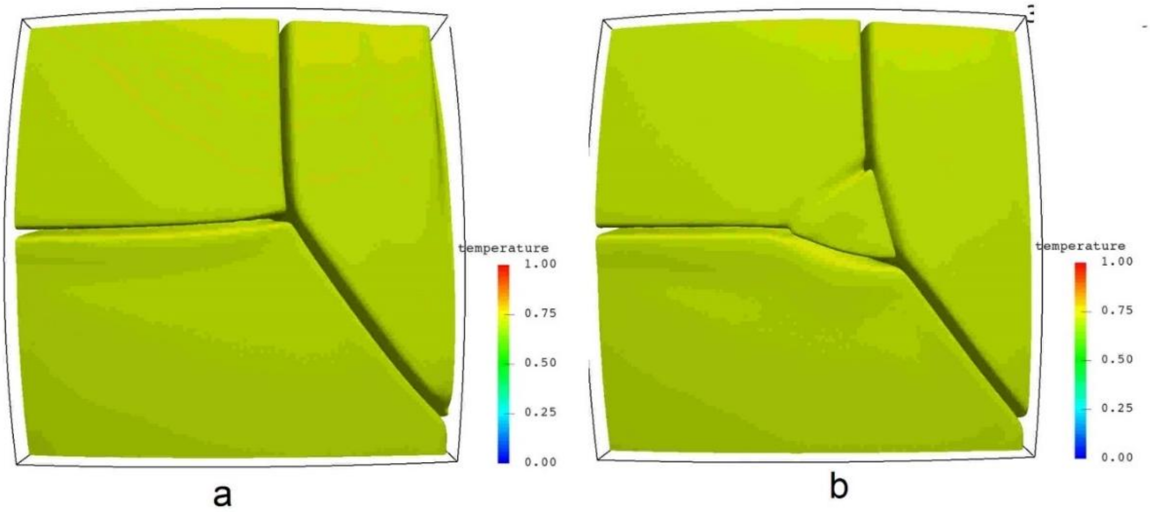

Fig. 3.7.5. Thermal evolution over a 38 Ma interval of the base of the lithosphere of a triple contact in the absence (a), or under the incidence (b) of a thermal anomaly (Besutiu *et al*., 2017).

The simulation suggested that an unstable triple junction can also occur under conditions of equal velocity for the three compartments of the contact when the base of the lithosphere is heated by a geothermal anomaly (e.g., a *mantle plume, or a thermal-chemical blob)*.

3.7.4. The role of thermal stress in generating earthquakes

A numerical simulation of thermal stress in the Vrancea area (Manea *et al*., 2009) showed clear correlations between the maximum stress zone and the area of the most intense seismicity.

Figure 3.7.6 presents the results of numerical modelling of the thermal stress generated by the sinking of the (colder) lithosphere into the higher temperature environment of the upper mantle, along a line crossing the East Carpathian Bend zone.

The concentration of intermediate earthquake foci within the zone of maximum stress is obvious.

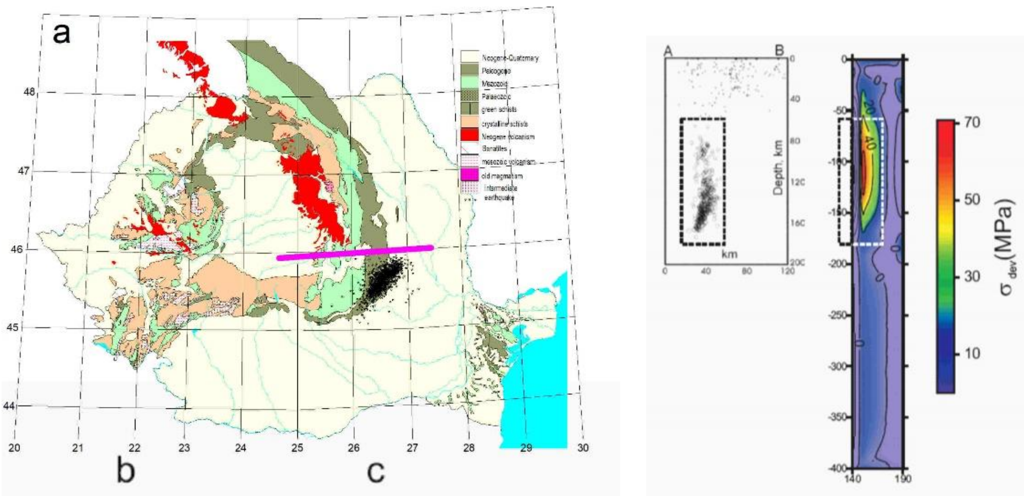

Figure 3.7.6. Distribution of thermal stress created by the sinking of a lithospheric compartment into the upper mantle, and the location of the hypocentres of intermediate earthquakes, along a profile crossing the East Carpathians bending zone (after Manea *et al*., 2009). a, location of the study line; b, projection of hypocentres; c, distribution of stress.

4. SCIENTIFIC COLLABORATIONS AND PARTICIPATION IN NATIONAL AND INTERNATIONAL PROJECTS

Besides research carried out within the frame of the priority program coordinated by the Romanian Academy, SEDD participated in a series of national and international projects and scientific collaborations that enabled the improvement of the research infrastructure and contributed to the development of the institute's visibility and prestige.

National projects

The SEDD obtained two grants from the Romanian Academy (GAR 96/2003 and GAR 92/2004) which allowed to carry out, in collaboration with specialists from the Institute of Geophysics and Geology in Chisinau, research to integrate the national geomagnetic standards of Romania and Republic of Moldova, and to build up consistent cross-border images of the geomagnetic anomaly on the territory of the two states.

Within a consortium led by IGSSS, including the Romanian Space Agency, S.C. Optoelectronica 2001 S.A., and S.C. CRUTA, a SME company, SEDD successfully implemented the project "Research through remote sensing of gravimetric, geomagnetic and geothermal anomalies for a better understanding of the processes taking place in the Vrancea seismic zone", funded by the AEROSPATIAL Program of the Romanian Research Agency, through grant 11024/2001–2003.

SEDD also carried out the MODEST project (Space-time modelling of the crust deformations within active geodynamic zones through the integration of terrestrial and space data), funded through the CERES grant 3–39/2003–2005. The project enabled, among other things, the construction of a network for geodynamic monitoring of the national territory, marking the beginning of a new research direction in Romania: study of non-tidal gravity changes.

INDEGEN (Intermediate Depth Earthquakes Genesis within Vrancea active seismic zone) was funded by the National Research Agency through the Research Excellence Program (CEEX-2/2006–2008), allowing the advancement of knowledge on the tectonic and geodynamic framework of the Vrancea zone, and the possible mechanisms for triggering the unusual seismicity in the upper mantle. IGSSS coordinated through SEDD the research consortium that included prestigious institutions from various fields: Geological Institute of Romania, National Institute for Earth Physics, Faculty of Geography at the University of Bucharest, and Faculty of Geodesy at the Technical University of Civil Engineering Bucharest.

The project offered the possibility of purchasing high-performance equipment for gravity observations. At the end of the project, a monograph was published (Besutiu, 2009) summarizing the results.

DYGEF (Research on the space-time dynamics of the Earth's magnetic field aimed at achieving consistent geomagnetic models over the Romanian territory integrated into European and Global framework) is another project funded by the National Research Agency through the Research Excellence Program (CEEX-2/2006–2008 X2C18), which allowed the rehabilitation of the regional aeromagnetic map of Romania and its integration into the international project WDMAM (World Digital Aeromagnetic Anomaly Map).

The research consortium, coordinated by the SEDD, included the Geological Institute of Romania (IGR), the Faculty of Automatics and Computers at Politehnica University of Bucharest (UPB), and the Faculty of Geology and Geophysics at the University of Bucharest (UB).

INSTEC (Integrated study of the post-collisional Miocene-Quaternary volcanic forms in the East Carpathians using geological and geophysical constraints) is a project developed in collaboration with another team from IGSSS, in which SEDD contributed in the field of geophysics, constructing models of the gravity field and the geomagnetic field in the area of the East Carpathians volcanic chain as well as some numerical models to simulate the sources of the gravity/geomagnetic anomalies outlined in the area (Besutiu *et al*., 2016a; Besutiu *et al*., 2016b; Besutiu, Zlăgnean, 2017; 2018; Seghedi *et al*., 2019; Besutiu *et al*., 2021; Besutiu, Zlăgnean, 2024).

International projects

SAFER (Services and Applications for Emergency Response) represents participation in a large-scale project funded by the European Union through the FP7 Space Programme, grant no. 218802/2008–2012 (EU EUR 26,912,700). SEDD worked within WP 30210 and 30220 led by INGV (National Institute for Geophysics and Volcanology in Rome) and had as main tasks the construction of a database for geophysical and geodetic observations carried out near the Earth's surface and the participation in the validation of the interpretation of satellite data regarding the dynamics of the Vrancea seismically active zone and the East Carpathian foreland between their bending zone and the Black Sea.

CYBERDYN (*Cyber-infrastructure for Geodynamic Studies Related to the Vrancea Seismogene Zone*) was carried out in collaboration with specialists from UNAM (National Autonomous University of Mexico), Dr. Vlad Constantin Manea (Project Director) and Dr Marina Manea and funded by the European Union through the Structural Funds Program (POS CCE O 2.1.2 contract 194/2010). The project allowed the construction of an advanced parallel computing system within IGSSS, the first infrastructure of this kind in the field of geosciences in our country. Its accomplishment created the circumstances for the implementation of numerical geodynamics in Romania (Manea *et al*., 2012a; 2012b; Pomeran *et al*., 2012; Besutiu *et al*., 2017).

In addition to these projects with a significant impact on the research infrastructure, SEDD participated in a series of bilateral scientific collaborations that contributed to increasing the prestige and visibility of IGSSS nationally and internationally.

The project "*Geodynamic evolution of the lithosphere within the south-East part of East Carpathians*" is a joint venture between IGSSS and EOST (Institute du Physique du Globe de Strasbourg). Within the framework of this cooperation, an integrated inversion of gravity and seismological data was carried out, which enabled the achievement of a seismic tomography for the Vrancea area at an unprecedented resolution (Tondi *et al*., 2009).

SEDD has maintained a long-standing collaboration with the Institute of Geophysics of the National Academy of Sciences of Ukraine (IG-NASU), resulting in a series of joint projects funded by both national academies.

TRIDEC (*3D modelling of the hidden structure of the crust beneath Alpine tectonics of the East Carpathians based on geophysical data interpretation, with emphasis on the Vrancea active seismic zone: geodynamic aspects*) was funded under a bilateral collaboration agreement for scientific cooperation between Romania and Ukraine in the period 2006–2007. The research included information exchange and the construction of common databases related to the East Carpathians area, across the state border between Ukraine and Romania, as well as direct field observations, aimed at creating a unified geomagnetic reference network. This network facilitated the integration of the two national geomagnetic standards. Rock samples were also collected from the East Carpathians, which are necessary for the geological interpretation of the geophysical anomalies outlined in the area.

DEEP (*Dynamics and Structures of the SW Margin of the East European Platform, as Inferred from Geophysical* Data) allowed the development of homogeneous cross-border images of the geomagnetic field in Romania and Ukraine (*Besutiu et al., 2005a; Besutiu et al*., 2006d).

LODES (Low *Danube Area Earth's Crust Structure from 3D Magnetic and Gravitational Modelling*) is another joint project between IGSSS Bucharest and IG-NASU Kiev, carried out from 2009 to 2011). The project enabled the creation of geophysical maps and interpretive cross-border models between Romania and Ukraine within the Lower Danube area, which were presented to the international scientific community (*Besutiu et al., 2015*).

INRAF (INtegrated Research of some Active Faults located in the NW inland of the Black Sea on the Romanian and Ukrainian territories) represents another joint venture between IGSSS Bucharest and IG-NASU Kiev, carried out in the period 2010-2012. The project also provided the opportunity to jointly conduct field observations related to the track and dynamics of the Peceneaga-Camena Fault (Besutiu *et al*., 2014).

ECEEC (*Structure of the junction between East Carpathians and East European Craton as inferred from magnetics and gravity modelling in the area of the geo-transect RomUkrSeism*) was to be carried out between 2016 and *2019*.

Unfortunately, the COVID-19 pandemic and then the war launched by Russia against Ukraine brutally interrupted this cooperation.

Collaborations with the industry sector

Occasionally, SEDD has also responded to some requirements of the industry sector in our country by concluding contracts with the private sector of the economy, such as the one with the company EMERSON S.A. from Cluj-Napoca, for the transfer of absolute gravity values to its industrial platform (P.O. 4262001330/ 11.02.2022).

5. AWARDS AND DISTINCTIONS

For the work carried out over time within the SEDD team or in collaboration with other specialists from the IGSSS or other institutions, the Romanian Academy rewarded the SEDD researchers with two "Ştefan Hepiteş" awards for the works by Mitrofan *et al*. (2016) and Besutiu *et al*. (2019).

Works published in international prestigious journals also received awards from CNCSIS: Mitrofan *et al*., 2021; Mitrofan *et al*., 2014; Mitrofan *et al*., 2010a, and the poster by Pomeran *et al*. (2012) was awarded the prize for the best paper by a young researcher at *the First International Conference on Moldavian Risks From Global to Local Scale*, Bacău, Romania, 16–19 May 2012.

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