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A POSSIBLE SLOW-SLIP-EVENT IN THE VRANCEA SEISMIC ACTIVE REGION OF ROMANIA

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Abstract. In the last 300 years the window of time for two consecutive large and destructive intermediate-depth earthquakes in Vrancea (Romania) was between 36 and 102 years. An explanation for the larger window of time might be a release of stress produced by a *slow-slip-event* (SSE). In a vertical sinking slab slightly attached from the Earth's crust both large earthquakes and SSE are expected to generate a downward movement in the vertical displacements of GPS data. The building-up of stress in the asperity preventing a steady aseismic sinking was expected to be transmitted upwards to faults in the crust and recorded based on a magnetotelluric phase splitting effect. A large stress build-up has been suggested around a fault in the years 2012–2013, but no large earthquake was recorded. We supposed a large SSE in the year 2013–2014 with a duration of 13 months released the accumulated stress. GPS stations in the epicentral region of Vrancea seismic active region supported our suggestion by showing a downward displacement of vertical data obtained for the year 2014. However, the vertical displacements are small and other possible causes than SSE need to be taken into account

Key words: slow slip event, seismic, stress, biolocation, geodynamics.

1. INTRODUCTION

Along a subduction-zone where an asperity prevents an oceanic plate to move under a continent the continental plate will store elastic energy. This stored energy can be released by an earthquake and as a result the continent will snap towards the ocean side. However, this is not the only possibility. A megathrust fault can simply slip aseismically at a rate similar or equal to the convergence rate, or *slow-slip-events* (SSEs) can accelerate spontaneously, but to proceed much slower than earthquake ruptures [1]. When GPS data show a snap of the continent towards the ocean with no earthquake attached, SSE can be defined in space and time. Also, in Japan [2] detected for the first time SSEs at a subduction-zone based on GPS data.

Back in 1910 [3] created an elastic-rebound theory explaining for the first time how an earthquake is produced. Sixty years later Plate Tectonics explained why earthquakes happen. However, the elastic rebound theory may be used to explain coseismic displacements but no creep and SSEs that are also part of the broad spectrum of fault slip.

Authors like [4] described SSEs that follows or precedes earthquakes as afterslip and preslip, respectively, and SSEs occurring between two large earthquakes as interseismic slip. In this respect [2] described first an afterslip event. An interseismic slip it is far more important. The relation between an interseismic slip and the next expected large earthquake represents a key question for hazard assessment. Eventually, in the future, inclusion of SSEs might be required in a time-dependent probabilistic hazard model for any seismically active region in the world. The first interseismic slip has been discovered by [5] in the deeper Cascadia subduction interface of North America.

Despite a large number of field observations based on GPS and modelling studies, the physical mechanism of SSEs remains elusive [6]. Most SSEs occur just downdip of normal seismogenic zone, but it is not clear why SSEs occur in a narrow, along-strike, patch of the subduction interface. Regarding the depth, and the physical mechanisms of SSEs' active at that depth [7] provided a compelling study. If a typical earthquake rupture velocity is 3.5 km/s, along-strike velocity of SSEs is 5–15 km/day [4]. In Cascadia [6] found rupture velocities for SSEs 1–2 km/day and 9–10 km/day, respectively. The same authors describe weeks-long up to year-long durations for SSEs.

The equivalent seismic moment of SSE is proportional to its duration but a linear scaling does not match with some recent observations. For instance, the analysis of the 10-year-long data set of SSEs from Cascadia suggests a cubic moment-duration scaling law, similar to regular earthquakes. Recent modelling results have shown that this cubic scaling arises because both simulated and natural SSEs have rupture velocities and stress drops that increase with magnitude [6].

SSEs are not confined to subduction-zones only. If the temperature-controlled rheology and friction conditions are right at a certain depth, SSEs can be generated along asperities for any fault type. It was no surprise that [8] discovered SSEs at depth in Central California along the San Andreas strike-slip fault. On this line of thought it will be no surprise that an array of GPS stations suggested a SSE in a sinking slab at an intermediate-depth in Vrancea seismically active region of Romania.

Modelling results from the Northern Apennines [9], also from subduction and collision zones show that lower crustal rheology and lithospheric mantle temperature modulate the crustal tectonics and the occurrence of fast and slow-slip-events. More than that, SSEs can be detected on low-angle normal faults, such as the Alto-Tiberina Fault.

2. A REVIEW OF HISTORICAL EVIDENCE FOR THE RECURRENCE TIME OF LARGE AND DESTRUCTIVE INTERMEDIATE-DEPTH EARTHQUAKES IN VRANCEA (ROMANIA)

Viewed in a planetary perspective the Vrancea seismically active region can be characterized by the persistence of large and destructive intermediate-depth earthquakes within an isolated small vertical slab of oceanic lithosphere situated in an intraplate environment far away from the active plate margins. The recurrence time of destructive events in Vrancea has been discussed among others by [10] and [11]. Also authors of papers [12] and [13] are known for their after-the-fact statistical earthquake predictions. When such predictions had been issued in real time they failed. One possible explanation of their failure might be that building up of stress between two large earthquakes has been regarded as continuous. The possible release of stress by SSEs was not known to be taken into account. Other recent statistical studies were realised for Vrancea using modern processing techniques, like ETAS [14].

The historical record of the past 300 years in the provinces of Moldavia, Muntenia and Transylvania contains valuable information for evaluating the earthquake potential in Vrancea seismically active area [11] described six large and destructive events in the year 1701, 1738, 1802, 1838, 1940 and 1977. The interseismic period has been between 36 and 102 years. A possible explanation for the larger interseismic period might be the release of stress produced by SSEs. However, no SSE was never mentioned in Vrancea seismogenic region.

Starting from the last large and destructive earthquake in 1977 and moving in time towards the past [11] remarked an alternance of shallower locations of about 100 km depth to deeper ones of 150 km. Since the 1977 event had a depth of about 100 km, his observation implies that the next expected large and destructive earthquake in Vrancea to be situated at 150 km depth. On the other hand, deeper locations are known to produce greater destructive effects towards the province of Moldavia and Transylvania when compared to a shallow one. All these observations might be suggestive and valuable. However, in order to prove them statistically significant a much larger number than six cases need to be taken into account.

3. BUILDING AND RELEASING STRESS IN THE VRANCEA SLAB AT AN INTERMEDIATE-DEPTH

The authors in paper [15] regarded the slab of oceanic crust in a vertical position in Vrancea, at an intermediate depth, to be slightly attached to the crust above by a so called “soft” coupling. The slab pull that created this strong elongation requires that the upper end of the slab is fixed vertically. The authors assumed that such a “soft coupling” is strong enough to enable elongation but weak enough to inhibit “quasi-static” stress transfer to the overlying crust. [6] discussed the rearrangement of forces due to slab breakoff. During the post collisional stage suction and mantle traction created bending and rollback of the residual slab. On the other hand, the remained slab elongated in a vertical position exerted a first order control on the motions, deformations and the seismic activity of collisional orogen.

In 1977, [16] suggested that faults in the crust can be mapped by biolocation and this method of investigation is related to the stress in the crust. The biolocation data are obtained as a human reaction when walking on a direction perpendicular to a fault-strike as detailed by [17]. The authors measured a distance “d” for the length of biolocation reaction obtained along the same path and across the same Horgasz fault in Covasna, Romania. The distance “d” showed variation against time, increasing, then sharply decreasing, before Vrancea intermediate depth earthquakes. The rate of increase was slower and the duration longer, for larger earthquakes. Sometimes the increase of “d” was continuous, but in 1976, before the 4th March 1977 Vrancea large earthquake (Mw7.2), the distance “d” showed oscillations across time with amplitude increasing and period decreasing during 6 months from May–November 1976.

They regarded the biolocation oscillation a precursor of the March 4th 1977 earthquake. However, the authors at that time could not explain the physical nature of biolocation and the possible relationship to the state of stress in the crust.

Later, [17] and [18] explained biolocation data across Horgasz Fault in Covasna as an effect of magnetotelluric phase splitting.

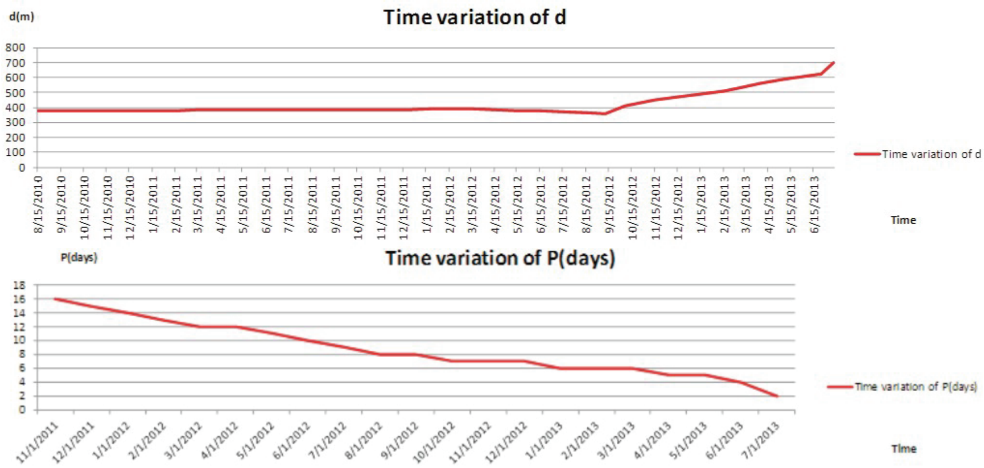

Fig. 1 – Oscillation for the amplitude (d) and period (P) of biolocation reaction obtained across Horgasz Fault in Covasna, Romania for the years 2012 and 2013.

By using biolocation data obtained during the years 2009–2013 across the same Horgasz Fault in Covasna [17] obtained for the years 2012 and 2013 a similar oscillation as in 1976, with amplitude increasing and period decreasing. Every day it was measured a distance “d” across the Horgasz Fault in Covasna from the fault strike to the end of the biolocation reaction. The biolocator is moving along a line perpendicular on the Horgasz Fault strike. He is measuring a distance “d” (Figure 1) showing how far away from the fault there are biolocation reactions. Then the distance “d” obtained daily is plotted across time. The increase of the distance for biolocation reactions obtained when moving across Horgasz Fault was attributed to an increase of stress in the Vrancea slab at an intermediate depth. The biolocation investigation continued at the end of 2013 and 2014 but no reactions have been obtained for 13 months. No large earthquake in Vrancea was recorded in 2013 and 2014. The lack of biolocation reactions for 13 months has been regarded as a large SSE.

Since the equivalent seismic moment of SSE is proportional to its duration, the SSE suggested in the year 2014 released stress equivalent to an earthquake with Mw around 7.

4. A REVIEW OF PSYCHOLOGICAL AND PHYSICAL INTERPRETATIONS FOR BIOLOCATION

Bio-location is known as a traditional form of mineral exploration with roots in the Middle-Ages. Bio-location is a body activity intended to feel a disturbance in the environment. Bio-locators are trained to react to disturbances above dry and wet caves and faults, salt domes and oil traps. During 1960–1990 geologists and geophysicists in the former Soviet Union correlated bio-location reactions to geomagnetic, resistivity and gravity anomalies, but no systematic correlation has been obtained.

Two experienced biolocators working independent from each other checked the reproducibility of the reactions. The location for the geological situation was unknown to the operator. When repeated along time the region with biolocation reactions obtained above a cave underground showed no variations. However, the same region obtained across a fault increased or decreased. The experiments suggested the stress field as a possible cause for biolocation reactions.

There is a lot of skepticism and confusion related to biolocation. While the nature of biodetection for mineral veins and faults seem to be a physical one, others consider a success to be related to parapsychology and name it a dowsing phenomenon. The vast majority of scientists consider dowsing an ideomotor effect and explain a possible success in mineral exploration as a scientific fraud only. In their view dowsing never works [19]. When scientists published papers showing positive results of biodetection in mineral prospecting they have been attacked by academia and forced to stop their research.

In the former Soviet Union geophysicists published in geological journals positive results of biolocation for prospecting oil fields, salt domes, caves in limestone, mineral veins and faults [20–22]. Scientists in the west ridiculed their work and disregarded their results.

It is true biodetection can be a self-suggestion and an ideo-motor effect for the vast majority of people. To make biolocation for mineral underground even more confusing, only a few talented and experienced prospectors are able to block their self-suggestion and obtain reproductible results in the field. North American Indians built large effigy mounds over places with biolocation reactions [23]. The largest effigy mound in North America with a bird shape was built about 1000 A.D. at Poverty Point, Louisiana, over a salt dome. Another large effigy mound with a snake shape was built in southern Ohio, along a fault strike and a mound with a bear shape can be seen over a cave in eastern Iowa in the Effigy Mounds National Park. When such biolocation reactions have been observed over time in Romania, their dimension in space has been constant for salt domes and caves. However, when measured across a fault strike, the length "d" of biolocation reaction increased for a while then decreased sharply before a large local and/or regional earthquake [17].

We need to look at the common physical anomaly for all geological situation able to generate a biolocation reaction. In 1992 [23] suggested a local variation of the stress field underground to be such a common anomaly. However, there is no physical instrument able to find a stress anomaly underground by moving the detector over the ground. Only a biolocator can do it.

In order to explain how a stress anomaly underground can be detected over the ground we need first to look at the methodology described by [24] for stress forecasting of large earthquakes. The author [24] had a new and revolutionary understanding of fluid-rock deformation in the distribution of stress-aligned and fluid saturated microcracks. They are so closely spaced that they verge on fracturing and hence can be regarded as critical systems. And critical systems impose fundamentally new properties when compared to conventional geophysics [24] created a New Geophysics. A consequence of the New Geophysics was that before a great earthquake at a subduction-zone, where the oceanic plate is moving under the continental plate, the stress can be transmitted over the continent from its active to the passive margin. The New Geophysics has been ridiculed and violently opposed by the established seismological community. In spite of such an attitude [24] has been able to perform successful stress forecasting before earthquakes.

Reliable stress forecasting requires three 1.5 km deep boreholes drilled at about 2 km apart one from the other. Two boreholes are placed along a fault strike and the third one has to be located perpendicular to the fault direction. A *down-hole orbital vibrator* (DOV) placed in one drilling situated on the fault strike radiates shear-waves to the other two drillings equipped with seismometers. Before a large earthquake the stress will increase along time and over a large area, including our fault under study. The shear-waves generated by the DOV will split around the fault and generate two different velocities, one along the fault and the other across it. The ratio of the two different shear-wave velocity will change over time proportional to the stress increase. This phenomenon is known as *shear-wave splitting* (SWS).

The methodology created by [24] and [25] based on SWS is costly and was not accepted to be implemented in Vrancea [17] and [18] proposed to use *magnetotelluric-phase splitting* (MTPS) in order to stress forecast earthquakes [26] showed that MTPS it is the electromagnetic equivalent of seismic SWS. MTPS can be used by biolocators moving above ground with no additional drillings and seismic equipment. Since MTPS can generate a biolocation reaction across the fault this effect has been used in our research for stress forecasting performed in Covasna on the Horgasz Fault in the years 1976–1983 and later during 2009–2020.

5. THE IMPACT OF GPS DATA FOR UNDERSTANDING THE GEODYNAMICS OF VRANCEA

The evolution of the oceanic slab that represented a remnant of the subduction of Thetis oceanic plate under Euro-Asian continental plate was described by [27]. It was believed that about 10 million years ago a fragment of oceanic slab, detached from the Earth's crust, collapsed into asthenosphere in a vertical position somewhere at the latitude of the Persani and Baraolt Mountains in Transylvania. During 10 million years the slab rolled back through the mantle reaching the actual position described in Figure 2 at the bending of Eastern Carpathians. This rollback is suggested by a line of seismic activity at a depth of 50 km from the Baraolt Mountains to Sfantu Gheorghe and Intorsura Buzaului [28]. It would be important to know that the line of seismic activity has been discovered by [28].

The properties of deep sub-crustal material are thus shown to influence (1) the long-term rollback and (2) the upper crustal seismicity in the orogen driven by slab retreat in and around the bending of Eastern Carpathians in Romania and even in regions with low-convergence rate such as the Central Alps, Del Zilio *et al.* (2020) [6]. The slab roll-back through the mantle pulled the upper crust with it, causing an extension and the formation of small sedimentary basins and faults. The Horgasz Fault in Covasna has been created in the last 10 million years as a result of roll-back. It is indicated in Figure 2 inside a small square [29] did not agree that slab pull and its lateral migration controlled vertical movements in the Focsani depression and suggested other possible causes.

The SSE was first suggested in the year 2014, when biolocation data showed a zero value for 13 months, released stress accumulated in the slab in the past. This interpretation has been supported by the fact of a low value for the amplitude of biolocation obtained across the Horgasz fault in the year 2015. However, our suggestion needs to be supported by physical instruments such as GPS stations situated in the epicentral area of the intermediate-depth earthquakes in Vrancea. More than that, most of the 13 km deep basin of Focsani depression has been created as a result of the slab pull combined with slab roll-back in a southeast direction [30]. That is why a series of GPS stations have been placed in the Focsani depression to check a possible downward displacement in the GPS vertical data.

In Figure 2, the Focsani depression is the region situated around the city of Focsani at the southeast limit of the epicentral area of Vrancea intermediate-depth earthquakes.

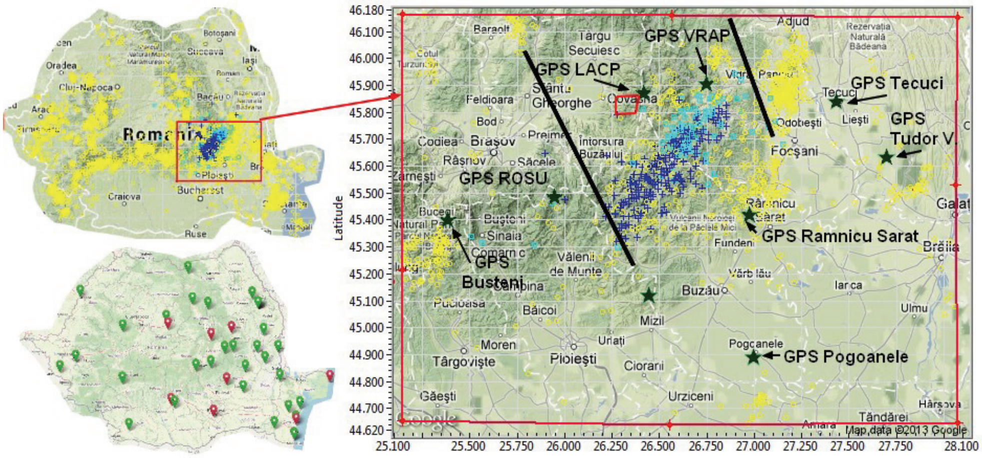

Fig. 2 – a. Seismicity of Romania; b. The GPS stations networks; c. The Vrancea seismically active region of Romania. The black lines indicate the roll-back of the slab in a vertical position from the latitude of Persani and Baraolt Mountains to the actual position at the bending of Eastern Carpathians. The red square indicates the location of Horgasz Fault in Covasna.

The network of GPS stations in Romania (Figure 3), expected very small vertical and horizontal displacements, since Romania is situated in an intraplate region far away from the plate margins of the Mediterranean region and the Anatolian strike-slip fault of Turkey. This being so, the Romanian seismologists took good care to place GPS stations of high accuracy. Permanent GPS stations have been chosen to enhance the noise reduction by averaging longer time spans and thus improving the sensitivity for vertical motions.

In order to prove the SSE of the year 2014 in Vrancea, the GPS data were processed with GIPS-OASIS v. 6.2 software using the *precise point positioning* (PPP) strategy [31], generating position solutions from each individual observation file. GIPSY is a state-of-the-art analysis tool, which includes a comprehensive suite of models to correct for all thinkable effects, ranging from wet and dry atmospheric distortions of the measurements to ocean loading displacements of the sites. The models are accurate to the 1-mm level. Accurate orbits and clock products were used from the *Jet Propulsion Laboratory* (JPL), as well as the wide lane ambiguity products, to invoke single-station ambiguity fixing. This results in so-called nonfiducial position solutions, which are in an arbitrary, internally consistent GPS orbit reference frame. These position solutions are then transformed into the latest International Terrestrial Reference Frame, currently ITRF2008 [32], using a global Helmert seven-parameter transformation also provided by JPL along with the orbits and subsequently, the individual site position solutions are grouped into daily combination solutions. In the next step, these daily solutions are converted to the fixed Eurasian reference frame by subtracting the motion of the Eurasian plate relative to ITRF2008, using the ITRF2008 rotation pole model for this plate. This yields time-series solutions of the position coordinates with respect to stable Eurasia. In the final step, the 3-D velocities are computed by means of linear regression of the position solutions of each individual site. Each dot is an individual estimate of site position, and the plot axes are scaled automatically to accommodate the data time span and range of position. For all stations time series are provided in IGS14.

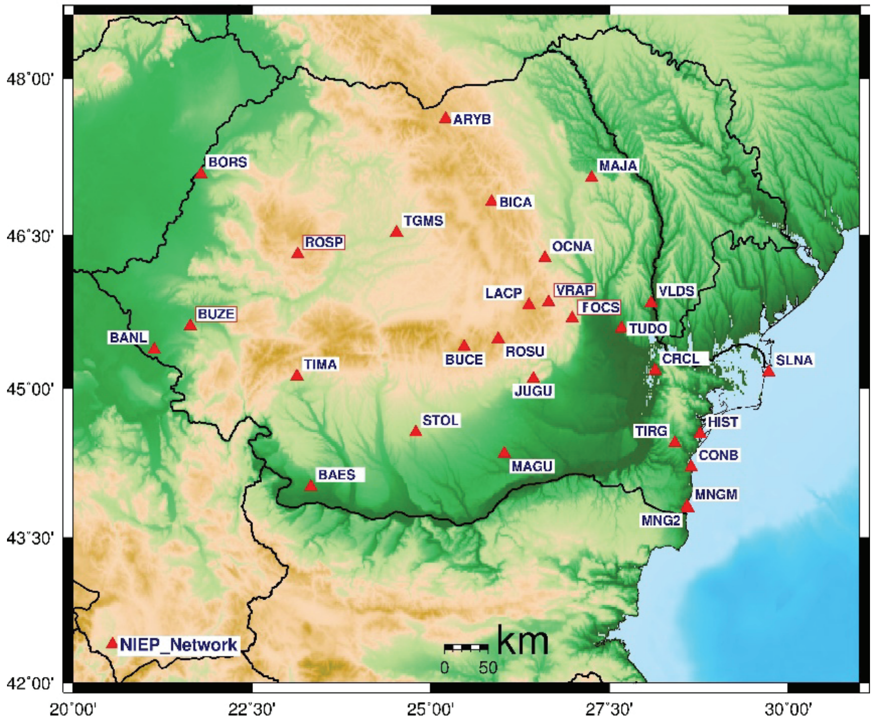

Fig. 3 – GPS stations in Romania – with red squares are marked the stations used in our studies.

We have analysed vertical GPS residuals from FOCS in the Focsani depression and at VRAP in the epicentral area of Vrancea intermediate-depth earthquakes at Plostina (Figures 4 and 5). We compared these GPS residuals data to site ROSP at Rosia Montana, in the Western Carpathians, 300 km far away from the Focsani and Plostina stations (Figure 6). The analysing period is of 5 years, from 2013 till the end of 2017 for all stations, and we have focused only on the vertical (radial) component. A 10 week running average of the residuals is plotted with a solid red line in Figs. 4 to 6, and helps to get a better idea of the trends in the three studied locations. The running average method smooths the data so that they become less noisy, and the interpretation becomes more reliable.

Most variations are probably due to local effects like groundwater levels and multipath of the antenna, and also variations caused during the winter time probably also caused by snow on the radome.

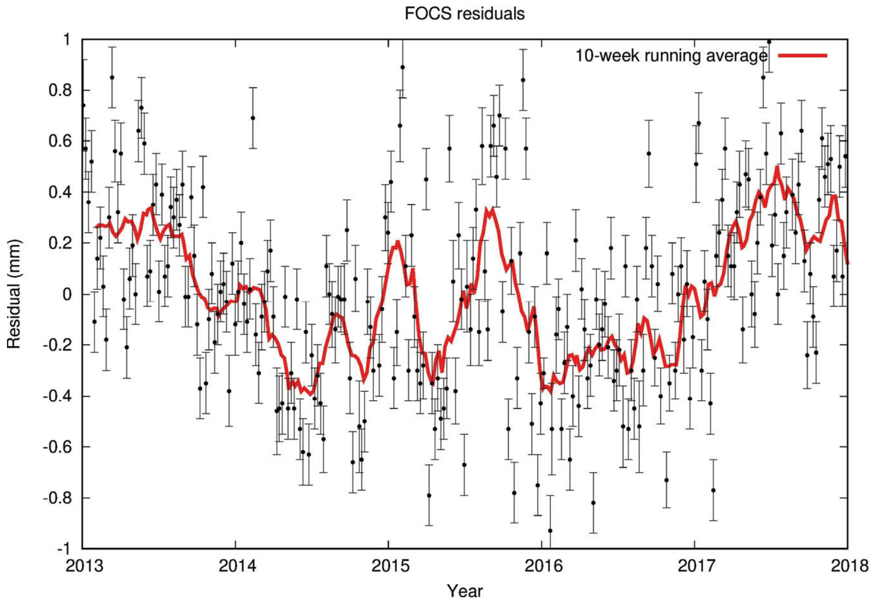

Fig. 4 – GPS vertical data at site FOCS.

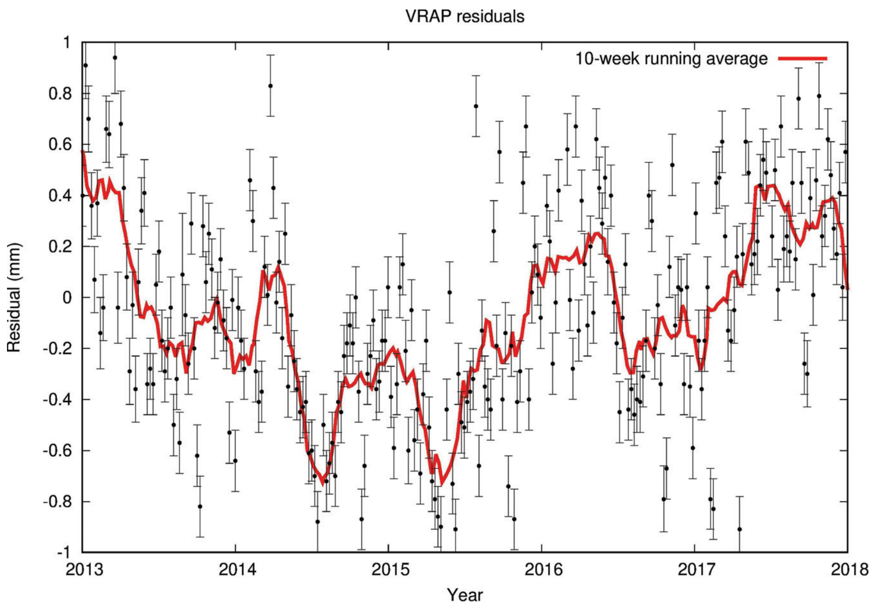

Fig. 5 – GPS vertical data at site VRAP.

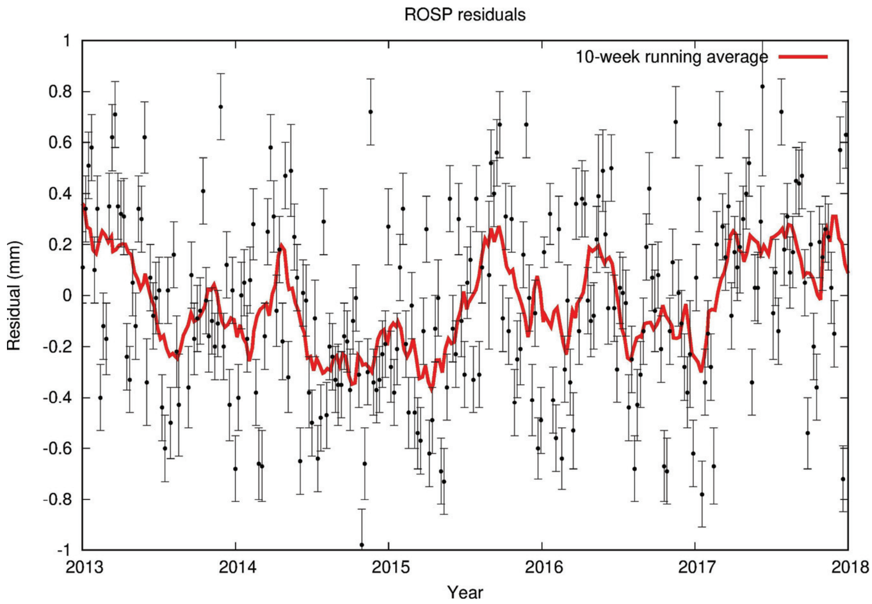

Fig. 6 – GPS vertical data at site ROSP.

During the studied period there have been recorded only 10 earthquakes with magnitude Mw larger or equal than 4.5, inside Vrancea zone, both at normal and intermediate depth (Table 1).

Table 1

Earthquakes with Mw>4.5 occurred in Vrancea seismogenic zone during 2013–2018

Nr. crt	Date/Hour (GMT)	Lat.° N	Long.° E	h (km)	Mw
Eq1	06.10.2013/1:37	45.67	26.58	135.1	5.2
Eq2	29.03.2014/19:18	45.6094	26.4709	134.4	4.6
Eq3	22.11.2014/19:14	45.8683	27.1517	40.9	5.4
Eq4	23.09.2016/23:11	45.7148	26.6181	92	5.5
Eq5	27.12.2016/23:20	45.7139	26.5987	96.9	5.6
Eq6	08.02.2017/15:08	45.4874	26.2849	123.2	4.8
Eq7	19.05.2017/20:02	45.7228	26.7547	121.6	4.5
Eq8	02.08.2017/2:32	45.5286	26.4106	131	4.6
Eq9	02.08.2017/2:32	45.5286	26.4106	131	4.6
Eq10	28.10.2018/00:38	45.6079	26.4068	147.8	5.5

For VRAP station can be clearly seen a downward trend from 2013 till mid-2014. The same observation is more or less true for FOCS. In comparison the ROSP does show variations but not a clear trend during 2013–2014. The location of GPS base station monitoring sites is presented in Table 2.

In fact, all studied GPS sites show variations in the red running average line (BUCE – Bucharest site and ZIMM – Zimnicea outside Vrancea zone and BUZE). The results on GPS data processing are presented in Table 3.

Table 2

Information on the GPS stations

Site information				Time span interval (yr)
STA ID	LONG (deg)	LAT (deg)	Heigh (m)	
VRAP	45.8513	26.6498	654.8	16.48
FOCS	45.7083	27.1946	97.4	7.72
ROSP	46.3169	23.1385	1228.1	11.22

Table 3

Results on GPS data processing

Site info	RMS of linear regression			Velocities relative to Eurasia			Velocity sigma (68 % confidence)		
STA ID	North mm	East mm	Up mm	V_ns mm/yr	V_ew mm/yr	V_up mm/yr	Sig_ns mm/yr	Sig_ew mm/yr	Sig_up mm/yr
VRAP	1.3	2.1	5.0	–0.73	–0.30	–0.09	0.05	0.08	0.19
FOCS	1.3	1.4	4.3	–1.13	–0.26	0.84	0.10	0.12	0.33
ROSP	1.4	1.5	4.1	–0.37	–0.61	–0.09	0.08	0.08	0.24

In conclusion, while the site ROSP had no downward trend, both sites FOCS and VRAP, seen clearer on VRAP, showed a depression of the vertical GPS data. However, the general trend from 2013 till mid 2014 might be related to the SSE.

6. CONCLUSIONS

The stress inside a slab in Vrancea, Romania, slightly attached to the crust, can be transmitted upwards and recorded around a fault by the magnetotelluric phase splitting effect. The stress oscillation obtained in 2012–2013, with amplitude increasing and period decreasing, has been regarded as a precursor of large SSE with duration of 13 months in 2013–2014. This interpretation was checked by GPS data. The vertical component of GPS showed a downward displacement for stations placed in the epicentral region of intermediate-depth earthquakes and in the Focsani Depression during 13 months in 2013–2014.

In the last 300 years the window of time for two consecutive large and destructive intermediate-depth earthquakes in Vrancea (Romania) was between 36 and 102 years. An explanation for the larger windows of time might be a release of stress produced by a *slow-slip-event* (SSE). The SSE in 2013–2014 disturbed the stress field in the Vrancea, so the time for the next large earthquake in Vrancea could not be estimated at present time.

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