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ORIGINAL ARTICLE

Development of SLO KARST Near Fault Observatory site in SW Slovenia

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Abstract

The project RI-SI-EPOS (Research Infrastructure-Slovenia-European Plate Observing System) provided new scientific equipment for solid Earth science related to geology, seismology, geodesy and karstology. Karst research infrastructure is primarily used at the SLO KARST NFO (Near Fault Observatory) developing site. The area covers ~ 2600 km^2 and is one of the most seismically active areas in SW Slovenia. It consists mostly of karstified Mesozoic carbonate rocks and partly of non-karstified Eocene flysch. The landscape has numerous karst features including caves, poljes, dolines, uvalas, karst springs, ponors and periodic karst lakes, with typical karst underground water drainage. Site development commenced with the installation of seven temporary seismic stations in the area, along with other geoscience equipment (gravimeter, 3D laser terrestrial scanner, GNSS antenna, TM72 extensometers, spectrometer for methane and drone), deployed in 2020. With the new dense seismic network, locations and other seismic parameters are already determined more reliably than in the past, contributing to a better understanding of active tectonic deformations at the junction between the seismically active Friuli region (Italy) and the Zagreb–Petrinja area (Croatia). The new solid Earth Geoscience research infrastructure is already collecting a big amount of data following the FAIR principles (making data Findable, Accessible, Interoperable and Reusable) aiming to be included in the national and international research databases. Here, the first results from the newly operating SLO KARST NFO temporary seismic network (May 2020–June 2021) are discussed.

Keywords SLO KARST NFO · EPOS · NW Dinarides · Slovenia

Introduction

Slovenia is a country with impressive karst areas (Blatnik et al. 2020), geologically situated between the Alps, Dinarides and Pannonian Basin, where there is moderate seismic activity (Placer 2008; Atanackov et al. 2021). Historically, strong earthquakes in this region occur in the most tectonically active areas related to the collision zone between the Eurasian plate and the Adriatic micro-plate (Burrato et al. 2008). The 1348 Villach/Carinthia/Friuli earthquake with a magnitude 6.4, the 1511 Idrija earthquake ($M = 6.8$), the 1880 Zagreb (Croatia) earthquake ($M = 6.2$), the 1895 Ljubljana earthquake ($M = 6.1$) and the 1976 Gemona (Italy) earthquake ($M = 6.5$) are the strongest historic earthquakes in Slovenia and neighbouring countries (ARSO 2021). In the most recent period, the destructive earthquakes in Zagreb (22 March 2020, $M = 5.2$ and $M = 4.6$) and in Petrinja (29 December 2020, $M = 6.4$) (Stein and Toda 2021; Markušić et al. 2021) must be mentioned.

Slovenia is an associate member of EPOS NFO (European Plate Observing System, Near Fault Observatories, https://www.epos-eu.org/tcs/near-fault-observatories) community with proposed SLO KARST NFO area (Chiaraluce et al. 2022) that includes Postojna Cave and the area south of Postojna in SW Slovenia to the border with Croatia near Jelšane (Fig. 1). It covers an area of about 2600 km^2 and is one of the most seismically active areas in Slovenia. The SLO KARST NFO area is situated within the Dinaric region, which is characterised mainly by sub-vertical faults with directions ranging between NW–SE (Dinaric orientation) and NNW–SSE, the most important of which are the Idrija Fault, Predjama Fault, Raša Fault and its auxiliary faults (Placer 1981). It is comprised mostly karstified Mesozoic carbonate rocks and partly of non-karstified Eocene flysch (Šikić and Pleničar 1975).

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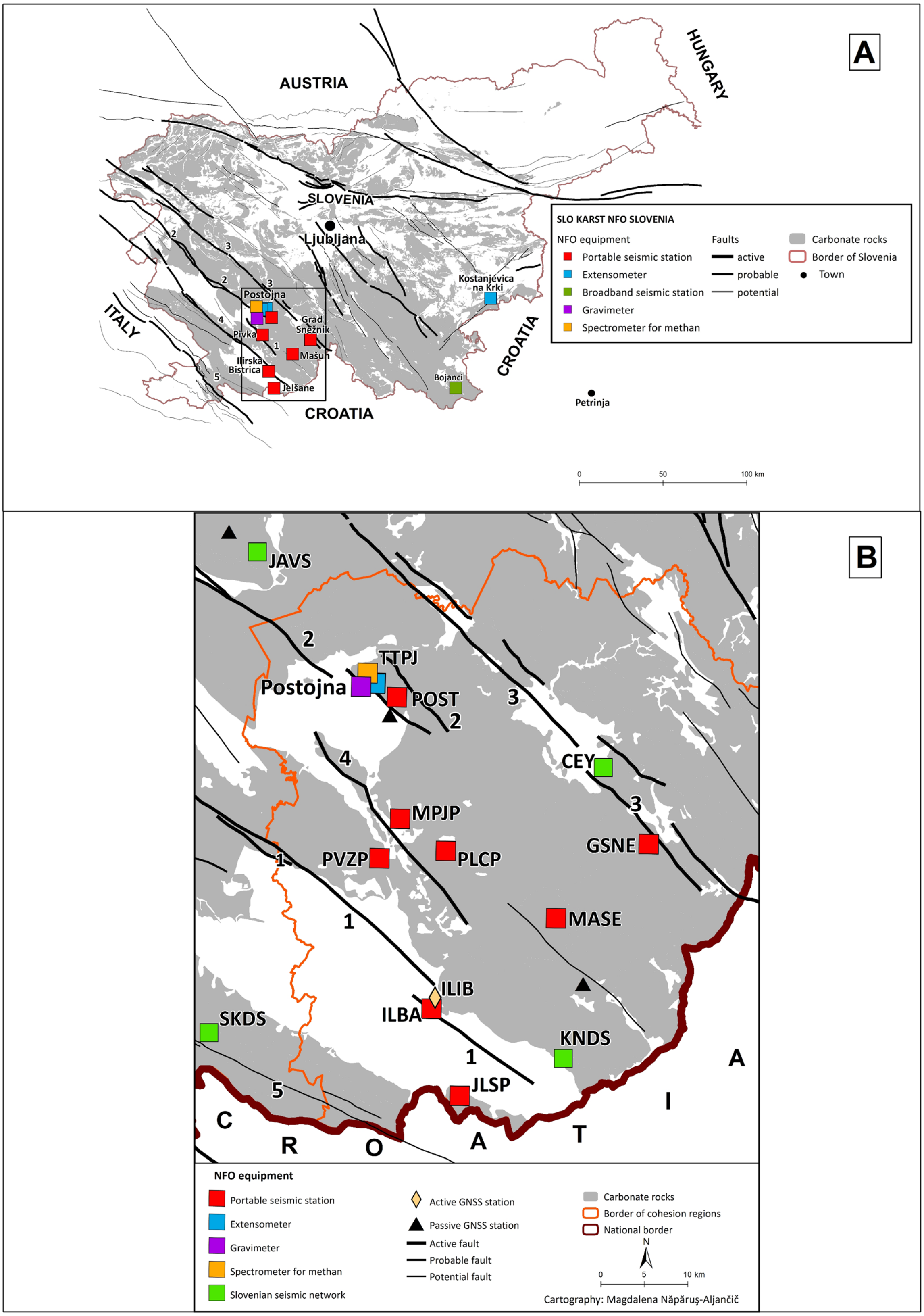
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2
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Postojna
Pivka
Grad Snežnik
Mašun
Ilirska Bistrica
Jelšane
Kostanjevica na Krki
Bojanci
Petrinja
SLO KARST NFO SLOVENIA
NFO equipment
Portable seismic station
Extensometer
Broadband seismic station
Gravimeter
Spectrometer for methan
Faults
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Carbonate rocks
Border of cohesion regions
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Cartography: Magdalena Năpăruş-Aljančič

◂**Fig. 1** **A** General position of Slovenia with active faults (Atanackov et al. 2021) and new RI-SI-EPOS research infrastructure equipment (https://arcg.is/0zuqn1). **B** SLO KARST NFO site located within the Eastern cohesion region with research infrastructure equipment. SKDS, KNDS, CEY and JAVS are permanent seismic stations (https://potresi.arso.gov.si/potresne-opazovalnice). ILIB is part of the SIGNAL national GNSS network (https://gu-signal.si/; https://www.e-prostor.gov.si/zbirke-prostorskih-podatkov/drzavni-prostorski-koordinatni-sistem/horizontalna-sestavina/stalne-postaje-drzavnega-omrezja-gnss-signal/). Faults after Atanackov et al. (2021) and Šebela (2005) 1-Raša Fault, 2-Predjama Fault, 3-Idrija Fault, 4-Selce Fault, 5-Skadanščina Fault

The strongest modern earthquake in the SLO KARST NFO area happened near Ilirska Bistrica in 1956 with a magnitude of 5.1 and EMS intensity VII (Vidrih and Godec 2006). In 1926, there was the Cerknica earthquake with magnitude 5.6 (EMS intensity VII–VIII) (Ribarič 1982), the location of which might be situated inside the proposed SLO KARST NFO site. On the Croatian side of the border, the strongest earthquake had the magnitude 5.6 Klana earthquake that happened in 1870 (Herak et al. 2018).

Moderate seismicity (magnitude 4.4 in 1995 at Ilirska Bistrica) and frequent earthquake swarm events (Vičič et al. 2019) are also present at SLO KARST NFO area. However, the earthquake locations are not so reliable that they could be attributed with certainty to any known fault in the NFO area. Before 2020, the area was monitored by four seismic stations of the national Seismic Network of the Republic of Slovenia (SNRS). To improve the accuracy of the locations and other earthquake parameters, the seismic network in the area was recently densified. In addition to the existing seismic stations of the national network, seven new ones were installed in 2020 (Fig. 1), in the frame of the project»Development of research infrastructure for the international competitiveness of the Slovenian RRI space — RI-SI-EPOS« (https://www.youtube.com/watch?v=NM1so88QNgc). The RI-SI-EPOS project promotes new research infrastructures (RI) in geosciences for the development of the Eastern cohesion region in Slovenia (Fig. 1B). In addition to new seismological equipment, other research infrastructure for geodynamic, geological and karstological monitoring of the NW part of the Outer Dinarides was provided and installed in 2020 as gravimeter, 3D laser terrestrial scanner, GNSS antenna, TM72 extensometers, spectrometer for methane and drone (Šebela et al. 2021a).

Moreover, one very broadband seismic station (owned by the University of Trieste, Italy) is installed in Postojna Cave (Fig. 1B, TTPJ) about 100 m below the surface (Živčić et al. 2014; Šebela et al. 2020) and has been in operation since May 2010. This increases the dimensions of the complex measurements in the Postojna Cave, complementing the collection of years-long data sets of micro-climatic [air *T*, air pressure, CO_2, CH_4, Rn, humidity, ventilation, etc. (Šebela and Turk 2011, 2014; Gregorič et al. 2014; Mlakar et al. 2020; Kukuljan et al. 2021; Šebela 2022)] and micro-displacement monitoring. In Postojna Cave, new TM72 extensometers have replaced older instruments as part of micro-displacement monitoring going on since 2004 (Gosar et al. 2009; Šebela et al. 2010, 2021b).

The SLO KARST NFO area holds passive GNSS stations (Fig. 1B) and one active GNSS station ILIB that is part of the SIGNAL national GNSS network (https://www.e-prostor.gov.si/zbirke-prostorskih-podatkov/drzavni-prostorski-koordinatni-sistem/horizontalna-sestavina/stalne-postaje-drzavnega-omrezja-gnss-signal/).

In addition to the area of Postojna (SLO KARST NFO), the SE part of Slovenia at the contact between the Dinaric strike-slip fault area and the Zagreb–Mid-Hungarian shear zone is also a subject of research. In this area, the new very broadband seismic station at Bojanci (BOJS), situated about 70 km SE from Postojna, was provided within the RI-SI-EPOS project (Fig. 1A). Data are transmitted to ORFEUS as part of the Seismic network of the Republic of Slovenia (https://potresi.arso.gov.si/potresna-opazovalnica/BOJS). In this same area, in Kostanjevica Cave (Kostanjevica na Krki on Fig. 1A), we have been monitoring micro-displacements with an extensometer since 2008. Significant vertical micro-displacement (0.35 mm in the period from 2008–2017) has been detected (Šebela et al. 2021b). Moreover, we also collect micro-climate data (air *T*, air pressure and radon) in the cave. Therefore, this location can contribute additional geophysical data to the developing SLO KARST NFO site.

The purpose of the new seismic stations is to detect seismic activity in the area south of Postojna and to use seismic data for studies of the geodynamics of the active tectonic structures mostly on karst area. With the dense seismic network, the locations and other seismic characteristics can be reliably determined for kinematic and dynamic studies of the active faults in this area. The strategic goal of seismology and karst geology within this project is to gain seismic and geologic data with the new equipment, to use the data with open access based on FAIR principles (make data Findable, Accessible, Interoperable and Reusable), and to expand the research related to processes in earthquake hypocenters and the geological structure of the Earth's crust in Slovenia and its neighbouring countries. Consequently, we want to contribute to a more accurate development of the seismic hazard map.

Slovenia has been part of the EPOS community (Cocco et al. 2022; Atakan et al. 2022) since 2010 and is also one of the establishing countries of EPOS ERIC (https://www.epos-eu.org/). The operation of RI-SI-EPOS is important for the development of the NFO site in Slovenia. Scientific cooperation between the Slovene scientific community (ZRC SAZU; Slovenian Environment Agency, Seismology Office; J. Stefan Institute) and foreign organisations (University of Trieste, Italy; ICTP-Abdus Salam International Centre for Theoretical Physics, Italy; and IRSM-Institute of Rock Structure and Mechanics of the Czech Academy of Sciences) has been taking place for many years and demonstrates an international interest for the development of SLO KARST NFO site.

In this paper, we present the technical characteristics and noise measurements of the new temporary seismic network located in the SLO KARST NFO site in SW Slovenia. Additionally, the first seismic and structural–geological analyses of earthquakes and related active faults detected by seven temporary seismic stations are discussed too.

Tectonic overview

Tectonically, SW Slovenia belongs to the Outer Dinarides (Placer 1981, 2008; Poljak 2000), located at the active contact between the Adriatic micro-plate and the Eurasian plate. Dinaric NW–SE-oriented faults and SW overthrusts are typical of the Outer Dinarides.

The Pivka Basin (Eocene flysch valley of the Pivka River), where three seismic stations are located [POST, MPJP (PLCP since 2 June 2022) and PVZP, Fig. 1B], is part of the Snežnik thrust unit to the north and the Komen thrust unit to the south (Placer 1981). According to Placer (1981), the Snežnik unit is part of allochthone and the Komen unit of para autochthone.

Although the area south of Postojna to the border with Croatia is seismically one of the most active areas in Slovenia, the question of which faults are tectonically active remains open. The regionally and morphologically well-expressed Idrija, Predjama and Raša faults (Atanackov et al. 2021; Moulin et al. 2014, 2016) are considered seismically active dextral strike-slip faults (Fig. 1). At the NW end of Predjama Fault, the horizontal slip rate is 1.6 ± 0.5 mm/year (Moulin et al. 2016). When averaged over the last 255 ka, mean slip rates of 1.15 ± 0.15, 1.45 ± 0.25 and 1.3 ± 0.2 mm/year are yielded along the Idrija, Predjama and Raša faults respectively (Moulin et al. 2016). Additionally, seismic swarms are typical for SLO KARST NFO area (Živčić et al. 2016; Vičič et al. 2019; Šebela et al. 2021b). At Postojna Cave, two episodes of vertical movement on a NW–SE-oriented fault are associated with earthquake swarms: the first episode was in 2010 ($M_{LV} = 3.7$) and the second in 2014 ($M_{LV} = 4.3$) (Šebela et al. 2021b).

In the Pivka Basin, the Selce Fault runs towards the SE to the western slope of the Snežnik Mountain (Gospodarič 1989; Poljak 2000; Šebela 2005). The map of active faults (Atanackov et al. 2021) does not show the Selce Fault as active. However, tectonic activity on the Selce Fault was studied by Vičič et al. (2019), who consider it as an active fault.

The Ilirska Bistrica seismic station (ILBA) is located within the Raša Fault zone (Fig. 1B). The Jelšane area (JLSP, Fig. 1B) is part of an approximately 1000 m wide belt of Cretaceous limestones with a Dinaric orientation (NW–SE). Towards the north there are Tertiary limestones and Eocene flysch rocks (Šikić and Pleničar 1975). This area is located between the Raša Fault to the north and the Skadanščina Fault to the south (Fig. 1).

The seismic station in Mašun (MASE) is located in the mountainous and forested area north of Snežnik Mountain (1796 m above sea level), where good structural geological maps are lacking. The seismic station at Snežnik Castle (GSNE, Fig. 1B) is located at the southern part of the Idrija Fault zone.

Although Dinaric-oriented strike-slip faults predominate as active faults (Atanackov et al. 2021), for the area SLO KARST NFO, we must not exclude the Snežnik thrust fault, as well as cross-Dinaric-oriented faults (NE-SW), which might also be active (Gospodarič 1989; Šebela 2005). In Postojna Cave, besides the Dinaric faults, the cross-Dinaric faults have also been considered as potentially active faults (Šebela 1998).

Characteristics of seismic research infrastructure and methods

Method for selecting the type of equipment

The initial approach to the choice of equipment type was based on the fact that the locations where the devices would be installed were not yet known. It was assumed that the potential locations would be in an urban environment where the expected average lower seismic-noise level may be significantly higher at frequencies above 1 Hz from Peterson's low noise model (NLNM, Peterson 1993) or the lower noise model for Slovenian territory (SI-LNM; Tasič 2015). The expected average lower noise level at potential sites was estimated based on analyses of three sites where long-period seismometers were installed and located in close proximity to urban centres. The seismic station KBZP is located in a house where people live permanently, the seismic station CESS is located on the outskirts of a small village, not far from the house but close to an industrial site, the site LJU is located on the outskirts of a medium-sized city (capital of Slovenia). Figure 2 shows the lower limit above which lies 90% of the power spectral density (PSD) data for the year 2020 for these seismic stations. For comparison, the Peterson noise models (NLNM, NHNM; Peterson 1993), the Slovenian low noise model (Tasič 2015) and the instrumental noise of three-axis accelerograph with a full-scale range of ± 2g are presented. The instrumental noise of the accelerometer

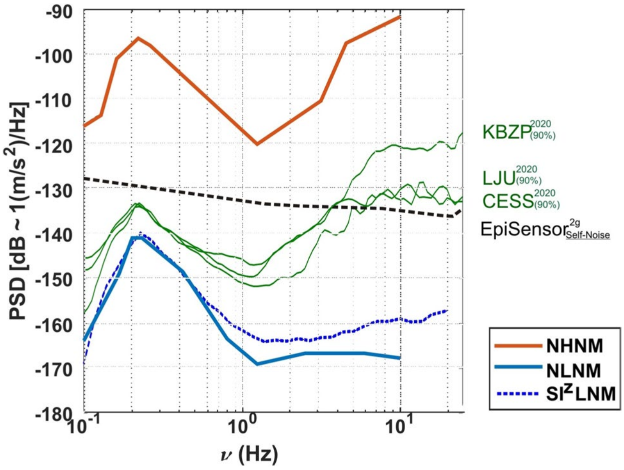

Fig. 2 The level above which 90% of 1-year PSD data of single seismic station are located. The green lines represent the area above which 90% of all PSD data are located for particular seismic stations (KBZP, CESS and LJU) that are at high frequencies in a seismic-noise sense amongst more-noisy in Slovenia (for the year 2020). For comparison, the Peterson noise models (NLNM, NHNM; Peterson 1993), the Slovenian low noise model (Tasič 2015) and the lower noise level of the three-axis accelerograph with a full-scale range of ± 2g, located in the BOJS seismic observatory are presented

is taken from the real data of the BOJS seismic station. At this location, the "2g" accelerometer is connected to the Q330HRS acquisition unit. Given the estimated low noise level of the three-axis accelerograph with a full-scale range of ± 2g (Fig. 2), this instrument can detect more than 90% of all seismic signals at higher frequencies at the (noisier) seismic locations presented above. The next guideline in the selection of instruments was based on the fact that it is unlikely that any structural interventions in terms of site improvement will be possible at potential sites. The base where the seismic instruments are potentially placed, could be connected to the rest of the site where occasional use of this location is expected. Since the base on which the potential seismological instrument is to be placed is unknown, and may even be a slightly uneven floor, a weak disturbance could cause an almost imperceptible slippage of the seismometer, proving to be a long-term response to the event record. Since accelerometers are clamped (bolted) to the ground, such disturbances are not expected with this type of instrument. The choice of the accelerometer as the measurement system was additionally influenced by past experiences. At some locations, where seismometer was not physically isolated or shielded from the rest of the room, unauthorised persons moved/rotated it without our knowledge. This directly influenced the measurement results. Since the accelerometers are fixed to the ground, such type of incorrections cannot occur.

Therefore, for all the reasons described above, the accelerometer was chosen as the measuring system. Due to standardisation with other measuring equipment in the Slovenian national seismic network, the measuring range was set to 2g.

Description of measuring equipment

Three-axis accelerographs with a full-scale range of ± 2g are installed at the POST, JLSP, MPJP (now PLCP), PVZP, GSNE and MASE sites (Fig. 3). ETNA2 is a compact three-channel accelerograph with smaller dimensions that includes three-axis accelerograph with a full-scale range of ± 2g, analogue to digital converters, and a processing unit that provides accurate timing of the data and takes care of local archiving and real-time data transmission to the Data Collection Centre. Each channel of the accelerometer is converted to digital form with a 24-bit delta-sigma A/D converter.

To protect the peripheral systems, three-axis accelerograph with a full-scale range of ± 2g is housed in a single housing (all in one box) along with the battery and power supply. The system also allows for partial placement of the accelerometer outside of this enclosure if required at a microlocation. Communication is transmitted via an LTE router or via a local WiFi system. Accurate time is given by the GNSS system, and receiver antennas are positioned in each of the sites in locations with an unobstructed view of the sky.

A set of instruments was obtained for a broadband seismic station including three-axis accelerograph with a full-scale range of ± 2g (Fig. 3). These instruments were deployed in Trillium seismometer at station ILBA. It replaced the previously installed ARSO seismometer at station BOJS.

Data from ILBA and BOJS are transmitted through national government network to ARSO Data Center and then replicated to ZRC SAZU. The GNSS system is also used for accurate time.

Seismic station details and telemetry

The seismic stations of the SLO KARST NFO temporary seismic network are located in different local environments. Most of them are installed in public institutions, one is installed in a private home. They are connected to local networks or to the Telekom wireless network through LTE modems. All stations are sending data in real time. The primary location for data storage is at ZRC SAZU Karst Research Institute in Postojna. Data acquisition and archiving are done through the software *slarchive* (IRIS 2022), which connects to the three-axis accelerograph with a full-scale range of ± 2g seedlink server and stores data on the archive server at ZRC. A secondary location for data acquisition is at the Slovenian Environment Agency (ARSO) which operates the Slovenian seismic network. Data acquisition is

Fig. 3 Seismic research infrastructure for the SLO KARST NFO site (POST, MPJP, PVZP, ILBA, MASE, GSNE AND JLSP) and for Bojanci (SE Slovenia, BOJS) installed in 2020. Figure 1 gives locations of individual seismic stations. Photos S. Šebela, M. Krebelj, M. Mali and I. Tasič

done by *orb2genc*, which connects to the three-axis accelerograph with a full-scale range of ± 2g ORB server (Object Ring Buffer) through *orb2orb* protocol (Antelope package 2022). Data from the SLO KARST NFO network is archived together with other Slovenian seismic stations data in ARSO archives and at the ZRC SAZU data centre. Phase picking and quality control are also performed at ARSO.

Seismic station MPJP (Table 1) was in operation from 15 July 2020 to 2 June 2022. Because the building, where the equipment was installed, is in renovation for longer period, we moved the instrument to new location at the Palčje village (Fig. 1B) and gave it the new name PLCP. It might happen that MPJP is premanently replaced with

Table 1 SLO KARST NFO site seismic station details

Station	Location	Institution	LAT [°N]	LON [°E]	Elevation [m a.s.l.]	Telemetry	Instrument	Start date	End date	Geology
POST	Postojna	ZRC SAZU Karst Research Institute	45.7756	14.2129	553	Local network	ETNA2	22 May 2020	In progress	Eocene flysch
MASE	Mašun	Private home	45.6290	14.3734	1043	Local network	ETNA2	13 August 2020	In progress	Cretaceous limestone
PVZP	Pivka	Park of Military History	45.6685	14.1885	559	LTE wireless	ETNA2	15 July 2020	In progress	Cretaceous limestone
GSNE	Snežnik Castle	National Museum of Slovenia	45.6829	14.4692	575	LTE wireless	ETNA2	26 August 2020	In progress	Cretaceous limestone
MPJP	Slovenska vas	Ecomuseum of the Seasonal Lakes	45.7011	14.2117	559	LTE wireless	ETNA2	15 July 2020	2 June 2022	Cretaceous limestone
JLSP	Jelšane	Elementary school	45.5008	14.2734	509	Local network	ETNA2	9 July 2020	In progress	Cretaceous limestone
ILBA	Ilirska Bistrica	Municipal office	45.5638	14.2446	404	Government network	CENTAUR + TITAN	1 September 2020	In progress	Eocene flysch
PLCP	Palčje	Elementary school	45.6762	14.2562	598	LTE wireless	ETNA2	2 June 2022	In progress	Cretaceous limestone

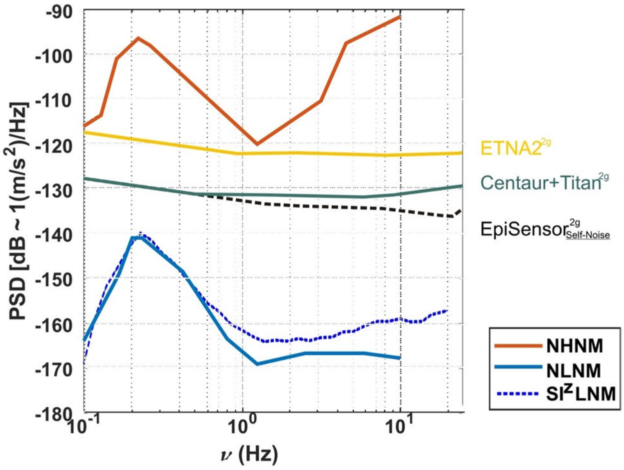

Fig. 4 The instrumental noise of the free-standing three-axis accelerograph with a full-scale range of ± 2g installed at BOJS seismic station (black-dashed), ETNA2 noise floor (yellow) and 'CENTAUR + TITAN' noise floor (green) are represented. The Peterson noise models (NLNM, NHNM; Peterson 1993) and the Slovenian low noise model (Tasič 2015) are also presented

PLCP due to better seismotectonic position and lower seismic noise.

Seismic events detected by the SLO KARST NFO seismic network for the period of May 2020 to June 2021 have been compared with contemporary databases of active faults in the NFO area (Šebela 2005; Atanackov et al. 2021; EDSF 2021). Furthermore, plots of the time versus magnitude, and depth versus magnitude, were created for all recorded events.

Results and discussion

Analysis and evaluation of device operation

The actual noise floor (PSD) for both types of seismic systems obtained from 1-year measurements (between September 2020 and September 2021) is shown in Fig. 4. Given the instrument noise of the free-standing three-axis accelerograph with a full-scale range of ± 2g from the BOJS site, our assessment of the applicability of the ETNA2 and 'CENTAUR + TITAN' instruments for weak signals at high frequencies was somewhat overoptimistic in seismic terms. It was based on the expectation that the dynamic ranges of the accelerometer and the A/D converter would be consistent. From the PSD plots (Fig. 4), it can be seen that the lower noise level defines the 'self-noise' or 'noise floor' of the A/D part of the instrument. The 'self-noise' of the ETNA2 unit is more than 10 dB noisier than that of the 'CENTAUR + TITAN' system. The difference is also evident in a direct comparison of

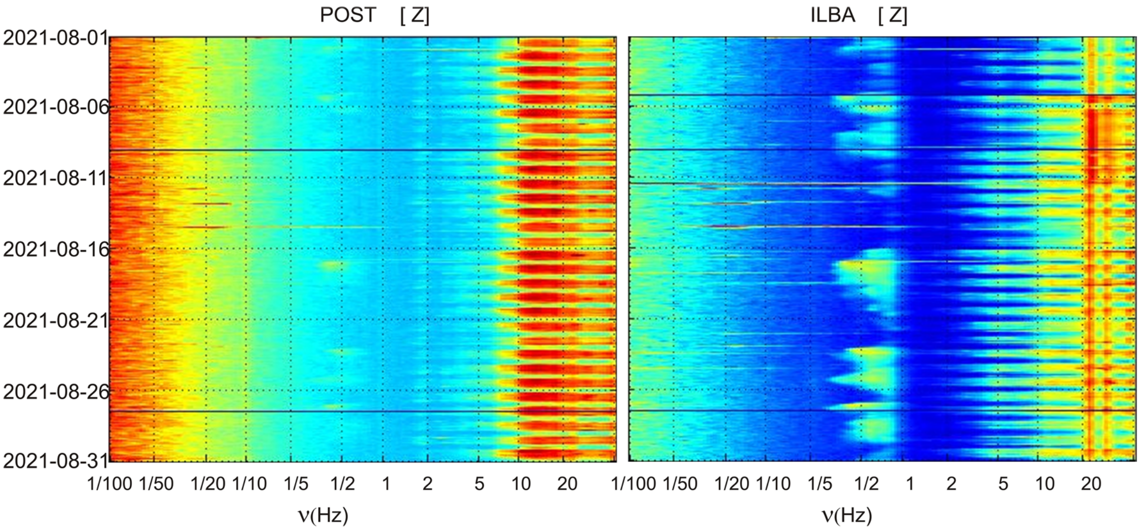

Fig. 5 Two-dimensional PSD plot of September 2021 for the location with the ETNA2 instrument (POST) and the location with the 'CENTAUR + TITAN' system (ILBA). Due to the lower instrumental noise of the 'CENTAUR-TITAN' system, seismic noise at 0.5 Hz can be easily detected at the ILBA site

the spectra with each other. Figure 5 shows two-dimensional PSD plots for September 2021 for location POST, where ETNA2 is installed and ILBA, where the 'CENTAUR + TITAN' system is installed. Due to the lower instrumental noise of the 'CENTAUR-TITAN' system, seismic noise at 0.5 Hz can be easily detected at the ILBA site. The miniaturisation of the ETNA2 seismograph equipment was assumed to be the main reason for the poorer detection of weak signals of the instrument.

Miniaturisation is also likely responsible for the weak disturbances found in the continuous recordings at 1-h intervals when the ETNA2 instruments were put into operation. It was later found that these disturbances occurred when seismological data were automatically archived, and a larger volume of data resulted in a higher system load and thus higher power consumption. When the archiving interval was reduced from 1 h to 20 min, the disturbances disappeared.

Initially, the ETNA2 instrument was also frequently interrupted, but it turned out that hackers were mostly responsible for these interruptions. But even after that was solved, short interruptions are still more common than the 'CENTAUR + TITAN' system.

However, a significant deviation was found in the measurement of the 'CENTAUR + TITAN' unit that persisted for 1 month. Strong teleseism can be used to control a relatively dense network of accelerometers. When the accelerometers are relatively close to each other, the perception of teleseism is relatively similar. Deviations from such a set of measurements indicate a deviation in the operation of a particular seismological device. For 29 July 2020 teleseism (Alaska M_w 8.2, Fig. 6), a significant discrepancy was noted in the data obtained from the ILBA site. Subsequent analysis revealed that on 5 July 2021, turning the instrument off/on caused the TITAN accelerometer to begin measuring in its "default" position (4g), and that when the instrument CENTAUR was upgraded on 5 August 2021, the power spike "corrected" the TITAN accelerometer's settings back to the requested values.

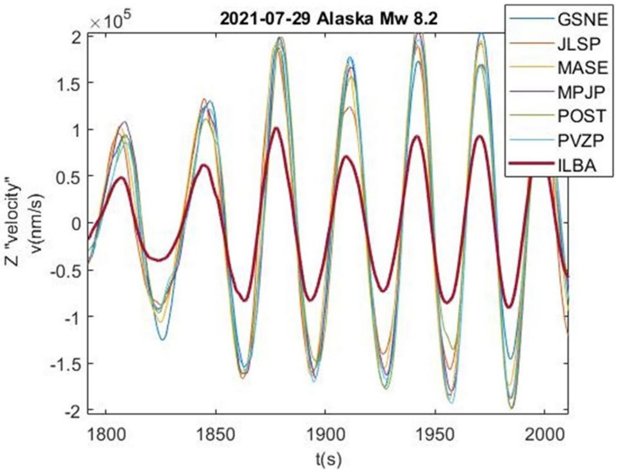

Fig. 6 Alaska earthquake on 29 July 2021 (M_w 8.2) detected by seven seismic stations at SLO KARST NFO site. Deviation of the instrument at location ILBA is clearly seen

All events are important, but the Petrinja earthquake (the location of Petrinja is marked on Fig. 1A) in December 2020 stood out because of the size of the earthquake. Such an earthquake is also a good test for the operation of the network, and all seismic observatories of the SLO KARST NFO successfully recorded the event (https://izrkp.zrc-sazu.si/sites/default/files/ri-si-epos_petrinja-martina_carman_12_febr_2021.pdf).

Seismic events and active tectonic structures at the SLO KARST NFO site

With the new research equipment, the SLO KARST NFO seismic network detected 201 seismic events between the period of May 2020 and June 2021 (Figs. 7 and 8). The majority of the recorded seismic events, a total of 150, were a magnitude 0–1; 46 events were a magnitude 1–2; and 5 events were a magnitude 2–3. In this period, no earthquake swarms were detected. Most of the recorded events on the new dense seismic network occurred in Slovenia, in the Pivka Basin and Snežnik Mountain. Besides the seismic activity in Slovenia, there is also considerable activity in Croatia, in the northern parts of the Gorski Kotar mountains.

The biggest seismic event in the considered period happened in the western area of Snežnik mountain on 13 May 2021 with magnitude 2.7. Intensity of this earthquake was IV EMS-98 and depth was estimated to 20.6 km and was well detected by NFO seismic network with peak accelerations ranging from 0.3 to 3.8 mg, which is well below the dynamic range of the installed instruments, which is set to 2g.

Three of the five highest magnitude events occurred in the northern parts of Gorski Kotar (Croatia). The second biggest recorded event had a magnitude of 2.4, and a hypocentre at the depth of 18.4 km. The rest of the substantial events that occurred in Gorski Kotar were of magnitude 2.0 and 2.2, both with depths greater than 15 km. The northern part of the proposed NFO is characterised

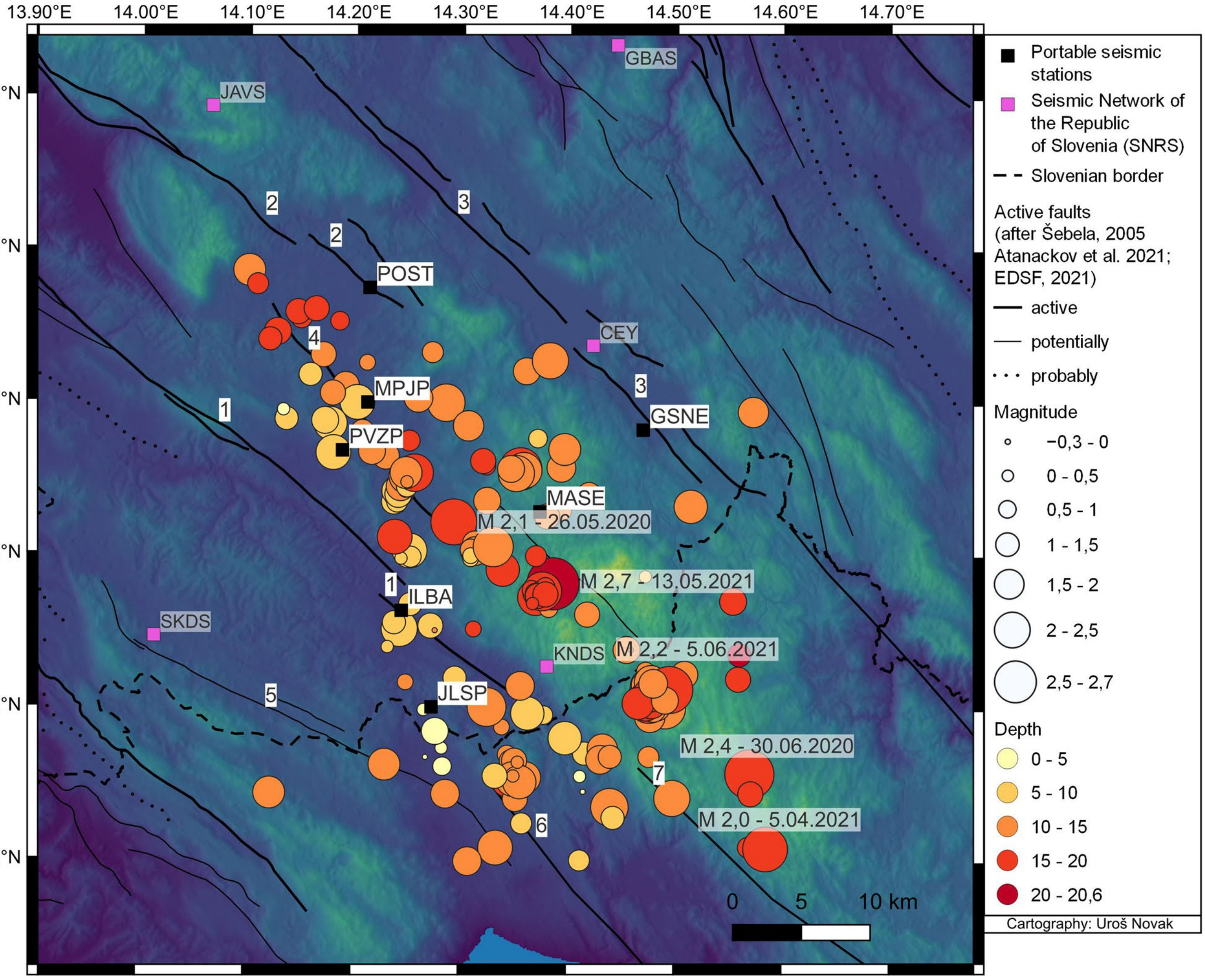

Fig. 7 Map of seismic events in SLO KARST NFO site with active faults in the period from May 2020 to June 2021. Active faults (Šebela 2005; EDSF 2021; Atanackov et al. 2021): 1-Raša Fault, 2-Predjama Fault, 3-Idrija Fault, 4-Selce Fault, 5-Skadanščina Fault, 6-Novi Vinodolski Fault, 7-Fužine Fault

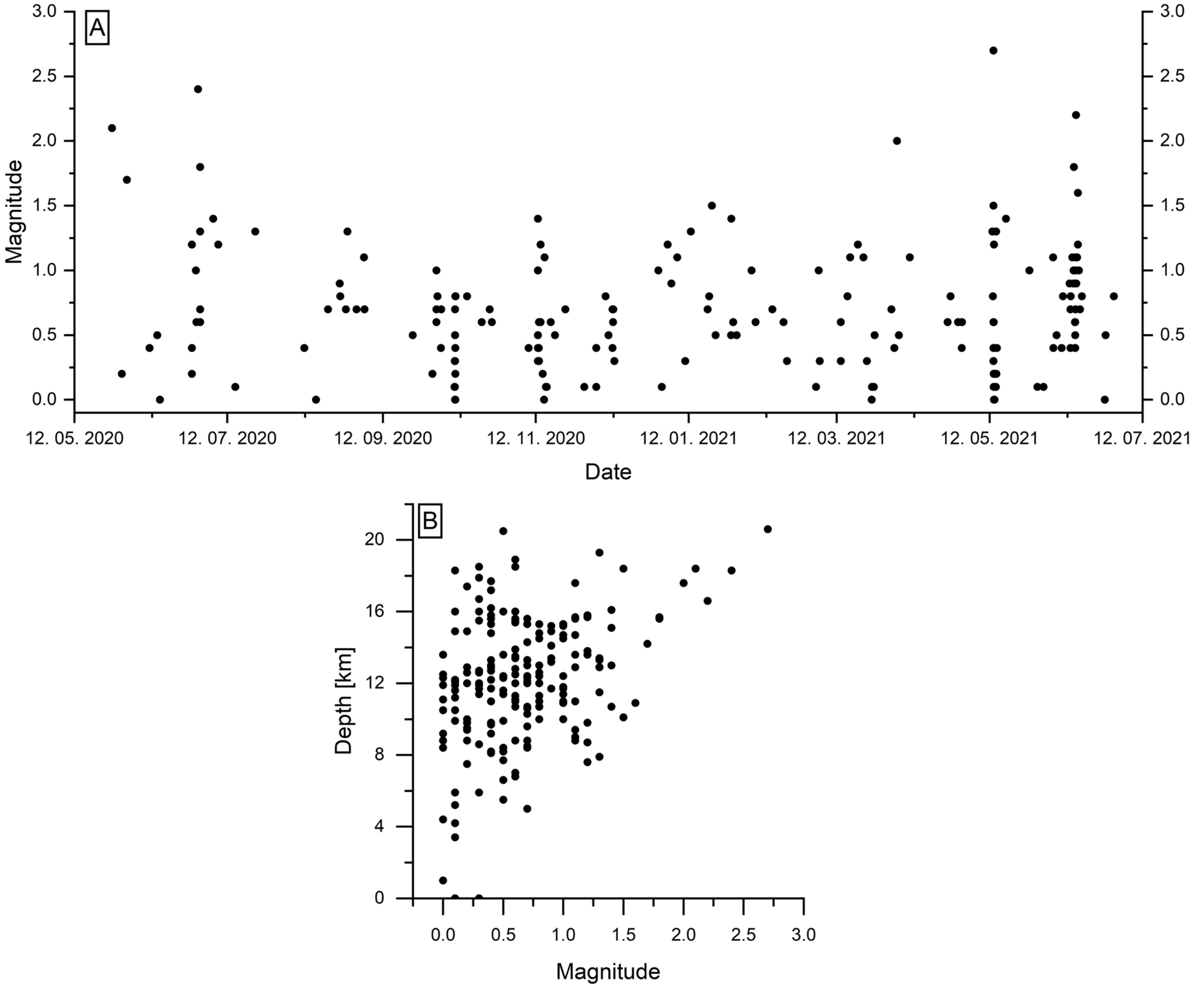

Fig. 8 **A** Relations between depth and magnitude of seismic events in the period from May 2020 to June 2021. **B** Time versus magnitude of seismic events in the period from May 2020 to June 2021

by seismic events that mainly occurred on the Selce Fault (Fig. 7). The highest recorded magnitude event of 2.1 had a hypocentre at a depth of 18.6 km and was located at the speculated southern termination of the fault trace. A small earthquake cluster was recorded at the northwest termination of Novi Vinodolski Fault (Fig. 7). All events were of magnitude 2–3 and had a hypocentre at depths greater than 16 km. The southernmost magnitude 2 + events seem to be affiliated with the seismic activity of Fužine Fault (Fig. 7). The two largest earthquake clusters, located on Snežnik Mountain and the northernmost part of Gorski Kotar, cannot be linked with certainty to a surface traced active fault at this time, due to the terrain's highly karstified nature and a lack of modern structural geological research in the area.

In the period from May 2020 to June 2021, Idrija and Predjama Faults did not show seismic activity and also Raša Fault showed less seismic events than Selce Fault (Fig. 7).

Conclusions

A new research infrastructure in the field of solid earth science was created in 2020 as part of the RI-SI-EPOS project (https://izrk.zrc-sazu.si/sl/programi-in-projekti/ri-si-epos). New seismic stations (7 temporary and 1 very broadband at Bojanci) extended the National Seismic Network of the Republic of Slovenia. The real-time data of the Bojanci station (BOJS) are already accessible through ORFEUS database. Data of the temporary seismic stations south of Postojna that belong to the developing SLO KARST NFO area will also be accessible as open data.

The first results obtained from operation (May 2020–June 2021) of the SLO KARST NFO temporary seismic network are the following:

- New seismic stations strongly help to better understand seismic activity in SW Slovenia and provide more precise earthquake data, which is important for the detection of active tectonic structures and contributes to seismic hazard maps.
- The instrumental noise of the installed compact seismic instruments at the SLO KARST NFO is higher than expected; but, on the other hand, the set-up of the instrument is simpler. Therefore, this is a compromise that must be accepted.
- The aim is that the temporary seismic stations remain permanently installed with some possible relocation of the research infrastructure depending on seismic-noise measurements.
- Weak seismic events (May 2020–June 2021) at the SLO KARST NFO site are aligned mostly along Selce Fault in the Dinaric orientation of NW–SE, which confirms tectonic activity in the wider Selce Fault zone. Idrija and Predjama Faults did not show seismic activity and Raša Fault also showed less seismic events than Selce Fault.
- South of the Slovenian border in Croatia, weak seismicity points to a continuation of the active Dinaric-oriented faults towards the SE and a probable interaction between Dinaric-oriented faults with other tectonic structures.
- The new equipment in the SLO KARST NFO site gives important information regarding active tectonics, not only for SW Slovenia, but also for neighbouring countries. The area lies between the recently very active tectonic territory around Petrinja and Zagreb (Croatia) and the tectonically active area in NE Italy and represents the junction between the NW Dinarides, Pannonian Basin and the Alps.
- With new research infrastructure, we are collecting a big amount of solid earth science data based on FAIR principles (make data Findable, Accessible, Interoperable and Reusable) with the aim to be included in national and international database centres.
- Important goal is to introduce karst research to EPOS community.

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