Development of operational seismology in Croatia

Croatian Seismological Survey

Department of Geophysics, Faculty of Science, University of Zagreb

M. Sc. Ines Ivančić

Head of the Croatian Seismological Survey

Croatian Seismological Survey

Croatian Seismological Survey was founded on January 1, 1985 at the Department of Geophysics, Faculty of Science, University of Zagreb.

- The Department of Geophysics, Faculty of Science, University of Zagreb hosts the **Croatian Seismological Survey**.

  - **Croatian Seismological Survey**
    - 8 seismologists, 1 IT and 1 technician
      (3 Ph. D., 1 M.Sc., 4 mag. phys.-geophys, 1 mag. ing. inf. et comm. techn., and 1 B.Sc.)
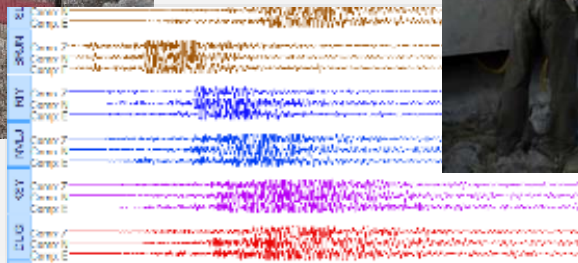
Law on seismological activities (1985)

Seismological activities are monitoring, registering and analysing seismic phenomena, collecting and processing data on the manifestation of seismic activity on land, structures and other objects, and seismological mapping. This law defines seismological operations of special social interest, as well as the conditions and manner of their performance.
(„Officiale Gazette", No. 44/85)

Seismological activities of particular social interest are:
1. **registration of earthquakes** and other seismic phenomena of natural or artificial source
2. establishment, maintenance and development of a basic **network of seismological stations**;
3. **collecting and analysing data** on earthquakes and other seismic phenomena, their causes and consequences;
4. Integration of seismological **mapping work**;
5. **seismic research and preparation of appropriate documentation** in the preparation of the spatial plan
6. submission of data on seismic phenomena to republican and municipal authorities and media;
7. **exchange of data** on seismic occurrences **with the relevant authorities and international seismological centers**;
8. **monitoring** of seismic phenomena related to the tasks of national and civil protection;
9. keeping **a seismological archive** with seismological documentation;
10. other activities of the seismological service in connection with the **insurance of the population and material goods**, which are defined by special laws as jobs of interest to the Republic.

Law on seismological activities (1985)

End Users:

1. Civil protection agencies,
2. Agencies for physical and urban planning,
3. Ministries responsible for seismic safety improvement and seismic risk management,
4. Authorities for seismic design code legislation,
5. National seismic networks,
6. Seismological, geological and geophysical institutions,
7. Insurance companies.

Croatian Seismological Survey

The Croatian Seismological Service (CSS) conducts **seismological research** in variety of fields.

Many projects necessitate close cooperation with scientists and researchers at the Department of Geophysics and CSS, as well as collaboration with researchers abroad.

The fields of research listed here highlight domains in which the CSS is particularly active:

- **Realtime Monitoring** - establishing a network of seismic stations in Croatia,

- **Seismicity in Croatia** - analysing, locating and quantifying earthquakes, archiving of digital data, macroseismic field work and analyses, bulletins, data exchange, cataloguing,

- **Historical Seismology**

- **Statistical seismology** - the distribution of earthquakes in space, time, and magnitude

- elaborating assessments of seismic activity in individual areas,

- **Strong Motion Seismology** & **Site-Specific Effects**

- performing tasks in the field of **earthquake engineering** and **engineering seismology** - includes producing catalogues of historical and instrumental earthquakes, local seismic hazard maps (microzonation) , link the results to data on building vulnerability so that dependable risk assessments can be carried out

DAILY AND URGENT

1. Maintenance and servicing seismological stations,

2. Determination of epicenter and magnitude of local earthquakes,

3. Estimation of intensities (effects of earthquakes),

4. Messaging - national protection and rescue directorate (112 duzs),

 - City office of emergency management (UHS),

 - Public media (local web site, radio, tv, newspapers...),

5. Sending data to CSEM (Strasburg),

6. Macroseismic data (MCS or EMS) acquisition by interview, phone, email,...

7. Working day: 7-21 public duty, 21-07 by emergency call from 112.

 Saturday: 7-14 public duty, sat. 14 - mon. 7 by emergency call from 112

Croatian Seismological Survey

URGENT

In addition to operating real-time monitoring infrastructure, on-duty seismologist react to detected significant events, providing rapid manual verification and notifying the Croatian authorities and media.

Online earthquake reports:

through the Web Questionnaires

http://www.pmf.unizg.hr/geof/seizmoloska_sluzba/izvjesca_o_potresu

Croatian Seismological Survey – organization

Seismo kolegium (all seismologists)

CSS-Head

Senior technician

Technician

Seismographic department

Accelerographic department

IT department

Department for macro, GIS, hazard and archiv

Instrumental Seismographic Section

Section for Seismogram Analysis

Subdivision for Seismogram Analysis

Instrumental Accelerographic Section

Section for Accelerogram Analysis

IT and Programming Section

Section for Communication

Section for Macroseismology

Section for GIS, Hazard and Archiv

IT Subdivision

IT Unit

Red: currently employed
Yellow: soon to be employed

A brief history…

Seismology in Croatia has deep roots that extend well into the 19th century: the beginnings of seismometry in Zagreb go back to the 1870's when Prof. Ivan Stožir placed a vertical pendulum 120 cm long, which wrote the motion of pendulum during an earthquake on the ash.

1879 – Dr. Mijo Kišpatić published "First comprehensive chronicle of earthquakes" (from 1502 – 1879)

1880 – the major Zagreb earthquake was the main impetus for the scientific study of earthquakes in Croatia

Seismology as a scientific discipline in Croatia started after the great *Zagreb earthquake of 1880* when the Academy founded **Earthquake Committee** (it's head was **J. Torbar**, and **M. Kišpatić** was in charge of collecting and analysing data. **A. Mohorovičić** later also joins the committee)

Zagreb seismological station

The gathering of instrumental seismological data in Croatia:

Andrija Mohorovičić

April 1906

- Mohorovičić established the **Zagreb seismological station** (*Vicentini-Konkoly* seismograph on loan from Budapest).
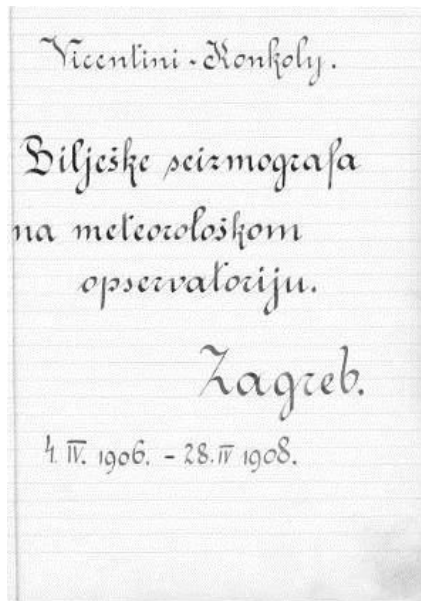
DIGITAL REPOSITORY at http://mohorovicic.gfz.hr

18 April 1906, San Francisco
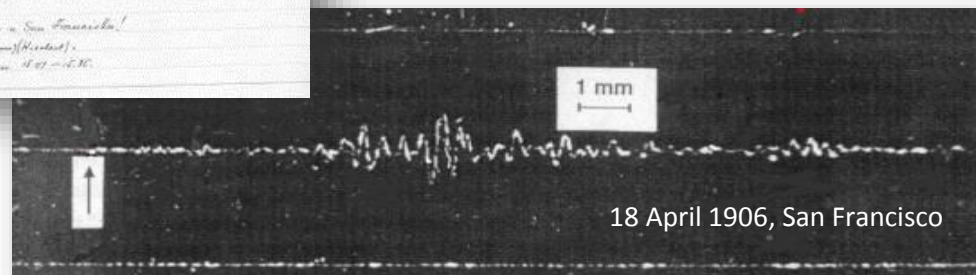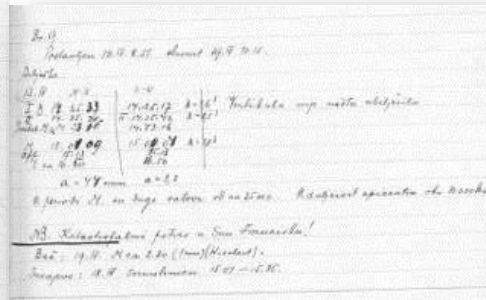
Herak, M., Allegretti, I., S. J. Duda (1996): Terra Nova

Zagreb seismological station

Continuous instrumental recording of earthquakes since 1908

Dissatisfied with the quality of Vicentini's seismograph, Mohorovičić soon acquired state-of-the-art instruments - Wiechert horizontal mechanical seismographs with a pendulum mass of 80 kg (January 1908) and 1000 kg (March 1909), which had a magnification of 220 times.
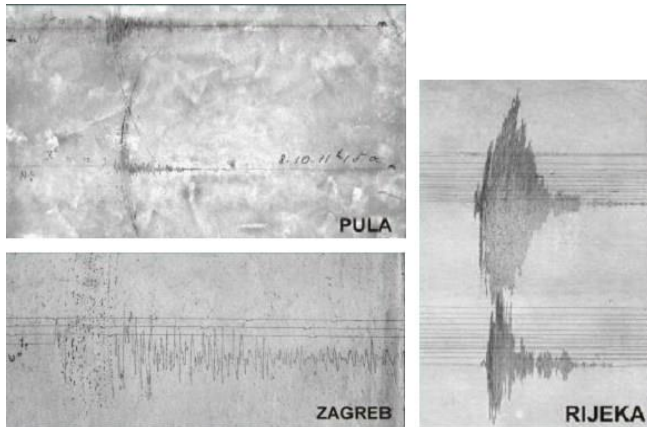
Wiechert mechanical seismographs

Year 1908
Small horizontal
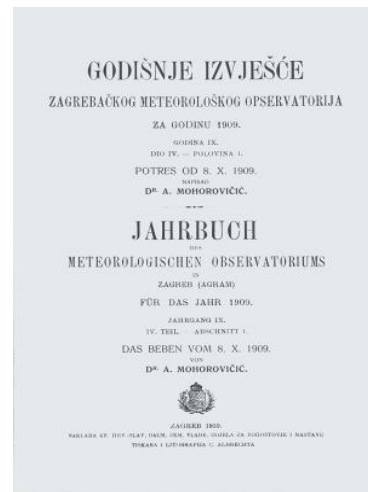mass 80 kg
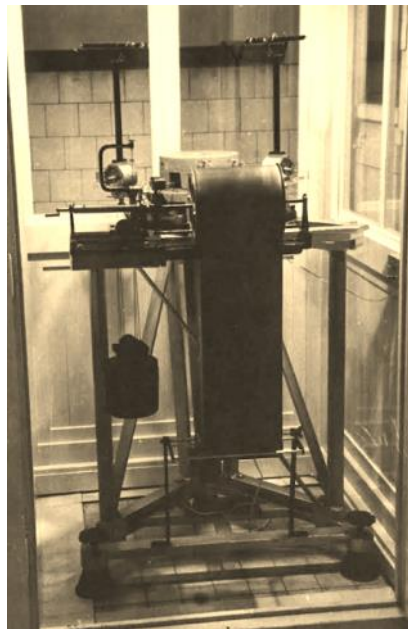
Year 1909
Large horizontal
mass 1000 kg
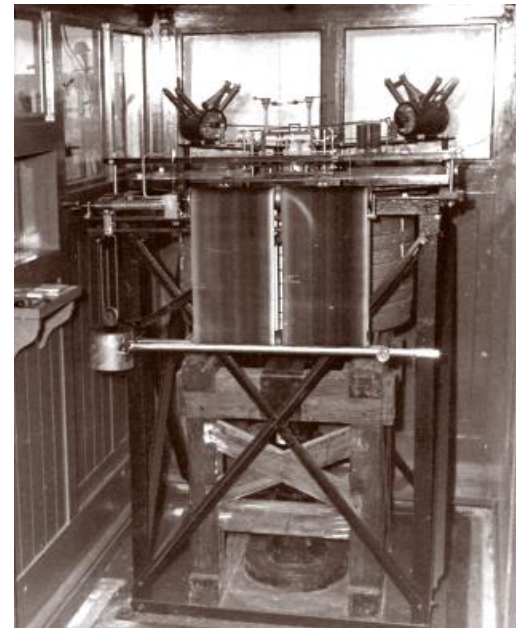
Zagreb seismological station

- **On Oct. 8, 1909** the new Wiechert seismographs recorded the **Pokupsko earthquake** (Kupa-valley)

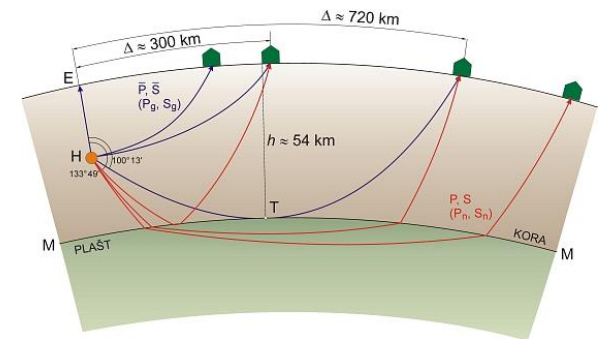Pokupsko earthquake, 8 October 1909

Mohorovičić's discovery of the discontinuity (1910)
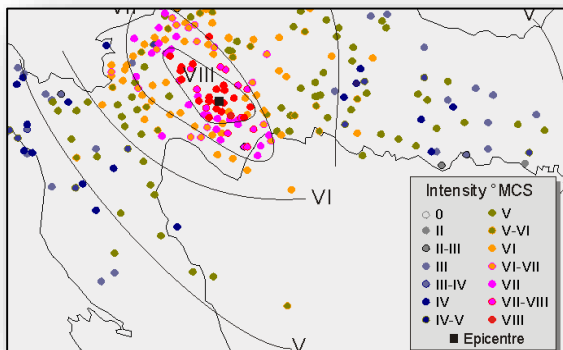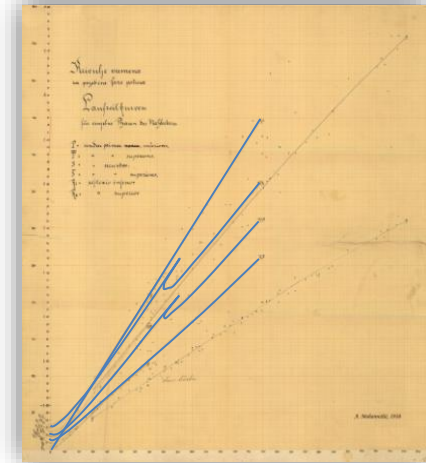
Herak, D., Herak, M. (2010): Seismological Research Letters

Zagreb seismological station – maintaining the accurate time

- Mohorovičić knew how knowing and maintaining the **accurate time** for seismology is extremely important

- He monitored the passage of stars through the local meridian with a passage instrument to correct the clocks (1892-1914).

- He acquired excellent observational swing clocks (*Riefler, Strasser, Siemens*)

- Since 1918, the clocks have been adjusted to the Paris and Nauen radio signal

- The Department of Geophysics emitted a signal of the accurate time until the 1990s

Zagreb seismological station

The Wiechert seismographs, along with the later acquired vertical instrument (1200 kg, also Wiechert constructions), served as basic seismographs in Croatia until the relocation of the Geophysical Section of the Faculty of Science to Horvatovac.
The last seismogram was recorded on March 27, 1984.

Today they have been renovated and exhibited in one of the memorial rooms of Andrija Mohorovičić.


A record of the May 6, 2011 earthquake that happened near Senj.

The red seismograms are recorded by a Wiechert seismograph on which the analog-to-digital converter is installed.

The blue is a seismogram of the same earthquakes recorded at the same location by a modern broadband digital seismograph.

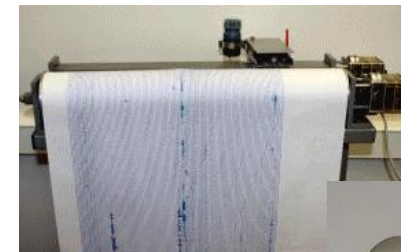# Croatian seismograph network – a brief history

373 BC-1907
975 earthquakes
(macroseismic data)

1908-1974
2680 earthquakes
(microseismic data)

Seismographic stations

1908
ZAG

1970
ZAG
LAB
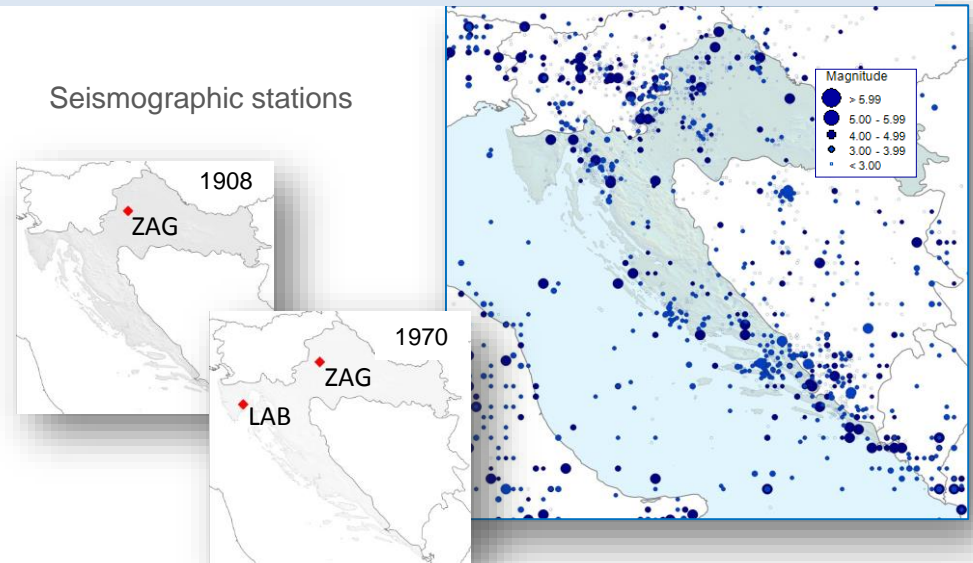
Zagreb (ZAG) seismological station is continuously recording earthquakes since 1908

- Until the sixties of the 20th century ZAG was the only seismological station in Croatia
- Electromagnetic seismographs (Sprengnether, SKM-3, Vegik) were obtained in early 1970-ies, in the framework of the UNESCO project "*Survey of the seismicity of the Balkan region*".
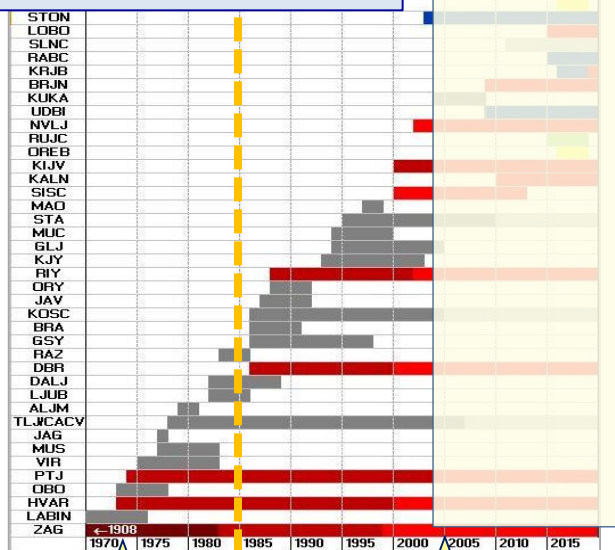- The new instruments were used to open new permanent stations Hvar (HVAR, 1972) and Puntijarka (PTJ, 1973)

Croatian seismograph network – a brief history

After 1975
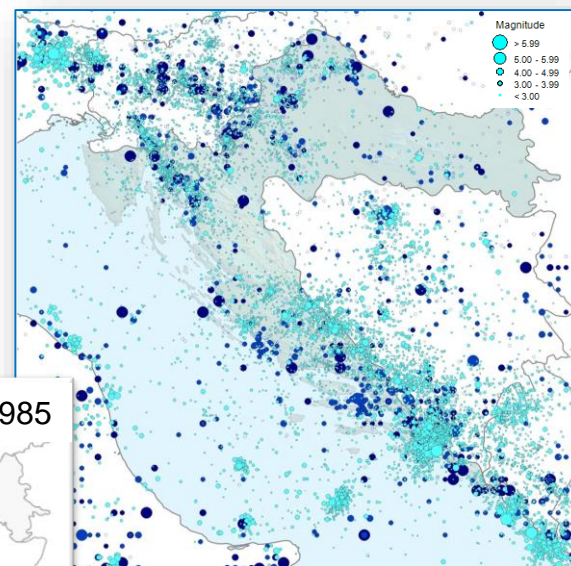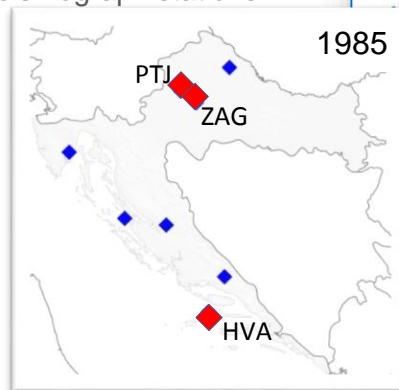
1975-2004
17718 earthquakes
(microseismic data)

Seismograph stations

1985
PTJ
ZAG
HVA

1975

1985

2005

Red: permanent stations
Grey: temporary stations (projects, contracts)
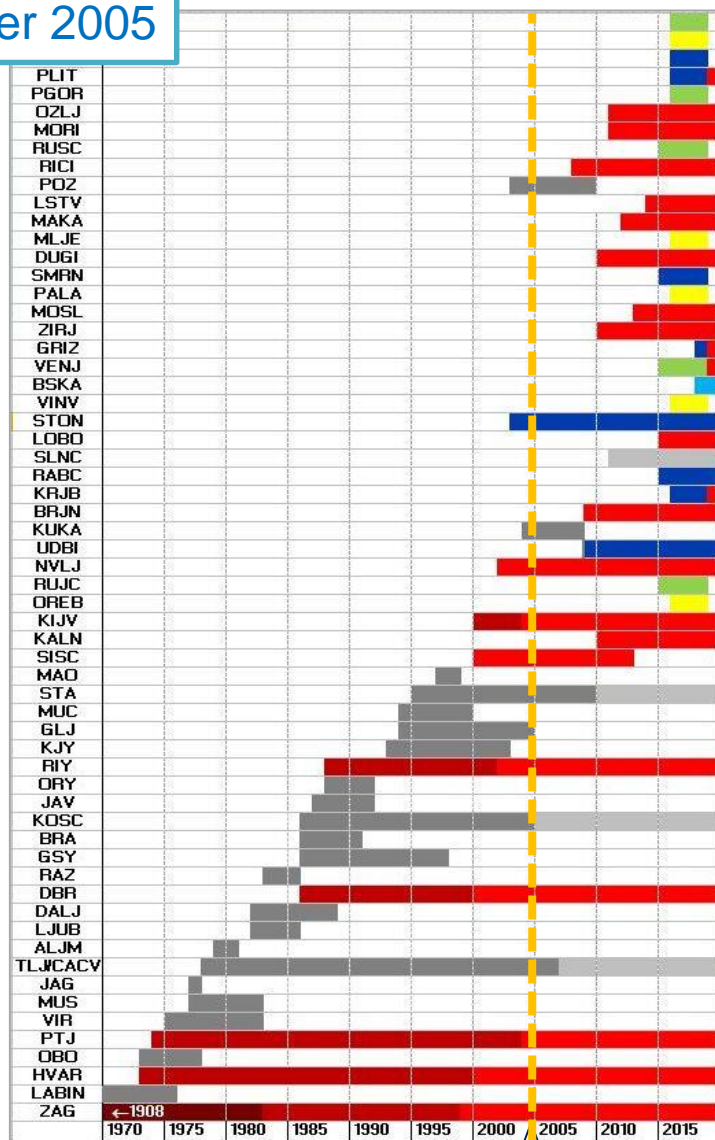(lighter shades– beginning of digital recordings)

1985: 3 permanent seismological stations: ZAG, PTJ and HVA
1989: modern broadband digital seismographs were installed at stations ZAG, HVA and DBK

Croatian seismograph network

After 2005

2005

Collection of earthquake related microseismic data is assembled by analysing seismograms recorded from permanent and temporary seismological stations in Croatia

- the number of seismographic stations increased

- seismographic stations were upgraded with installation of digital equipment

- All stations broadcast data to the central facility in Zagreb in real time.

Red: permanent Croatian State Seismological Network
Grey: temporary stations (projects, contracts)
(lighter shades– beginning of digital recordings)

Blue, green and yellow - temporary stations installed within two Croatian research projects 2016-2018 (*Velebit* and *AlpArray*)

Croatian seismograph network
## Stations and their locations, as well as the sub-networks they operated within

Today the Croatian Seismological Network consists of

- the permanent Croatian State Seismological Network run by the Croatian Seismological Survey, and its Zagreb-Net subnetwork (operating instruments owned by the City of Zagreb),

- the stations installed within two Croatian research projects
  – *Seismicity of Croatia* (2006–2013), funded by the Ministry of Science, Education and Sports, and project *VELEBIT* (2015– May 2019) funded by the Croatian Science Foundation.
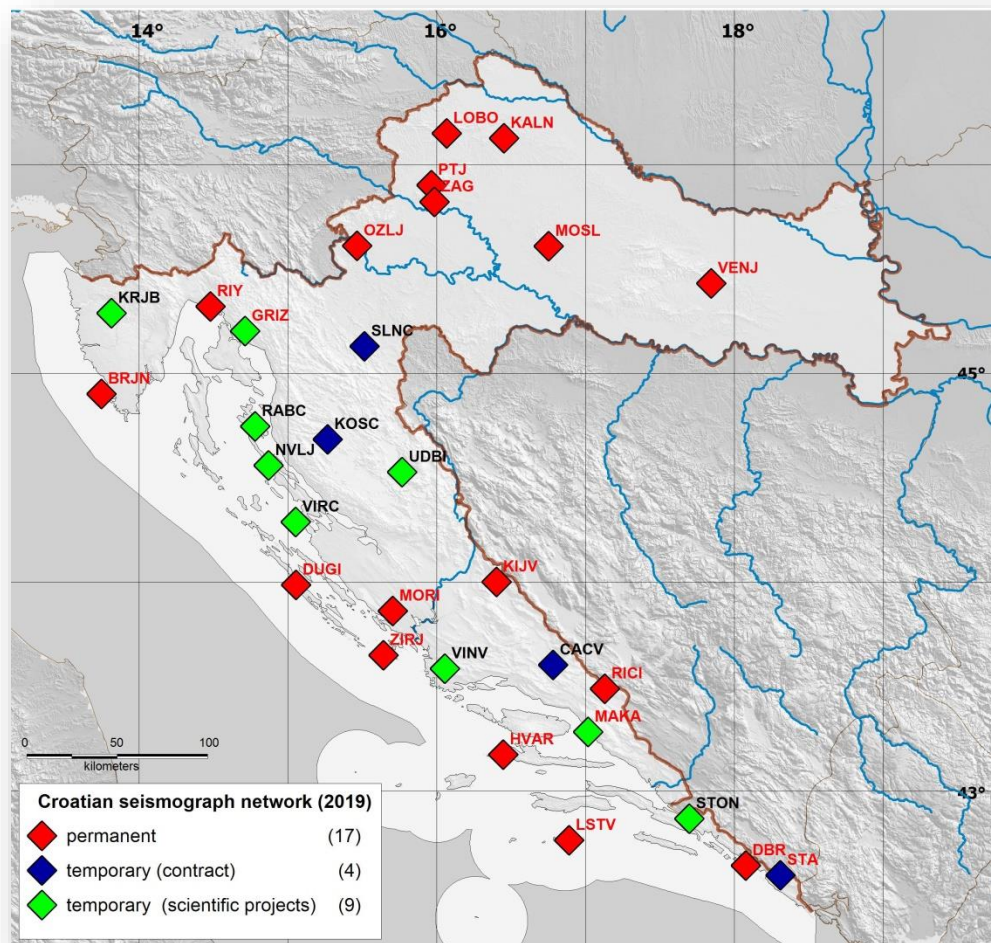
Croatian seismograph network - permanent seismological stations

- CSS permanent stations: 17
- Strong motion: 12

- Croatia - total land area:
    56.594 km²

- 1 station on 3300 km²

CSS permanent stations (17)
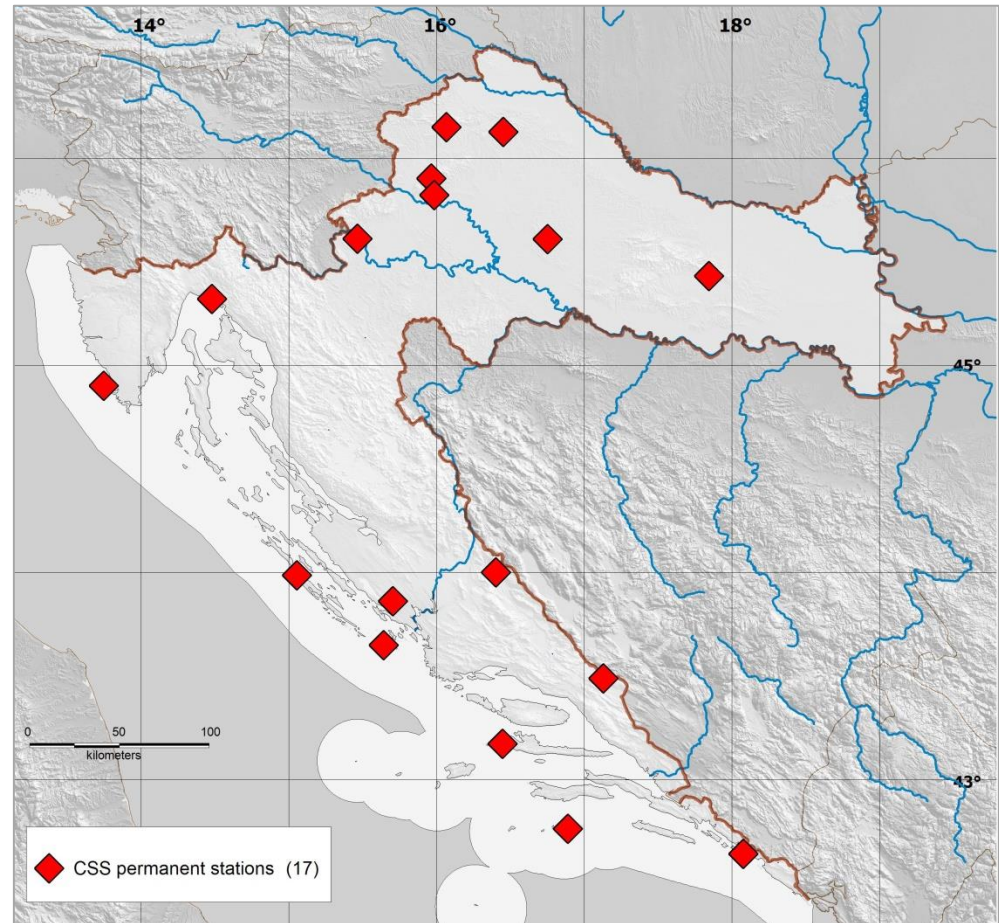
Croatian seismograph network

The Croatian network relies mostly on BB Güralp instruments, with the exception of two Lennartz and two STS-2 seismographs:
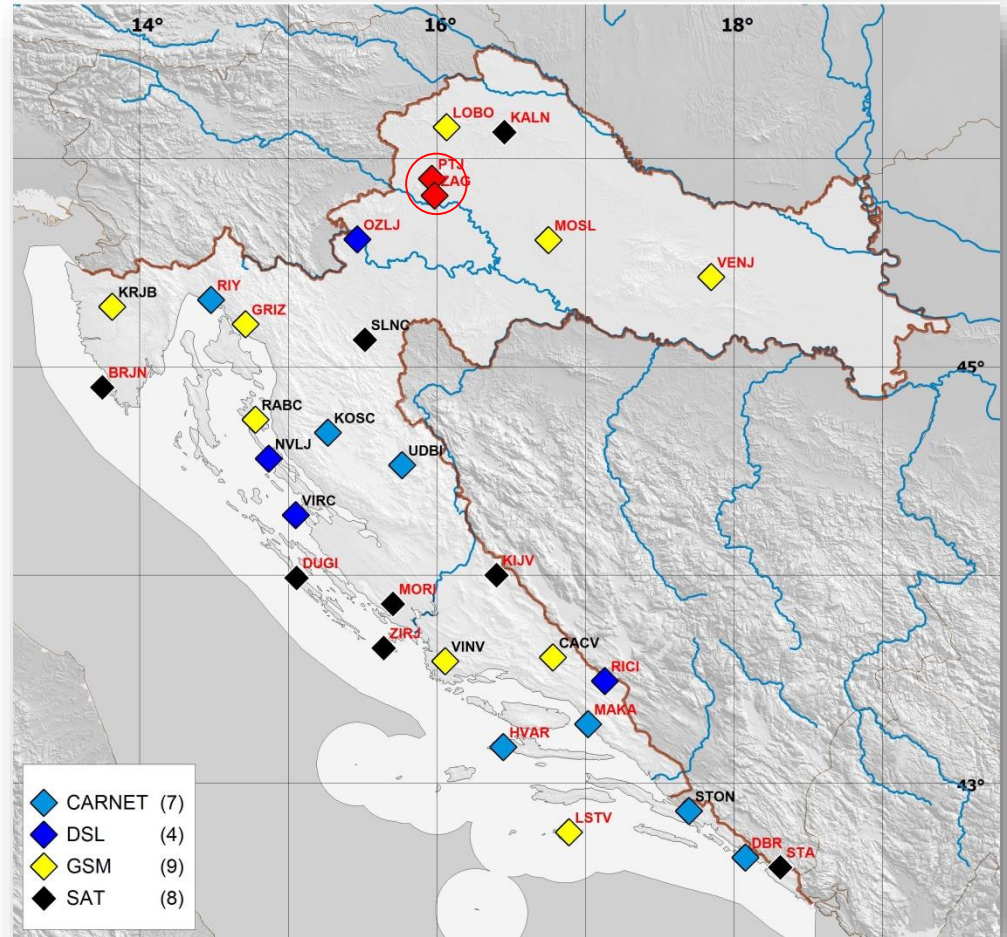
Lennartz - SCREAM

Lennartz & Guralp – SCREAM

STS-2 & Q330 & - SeiSComP

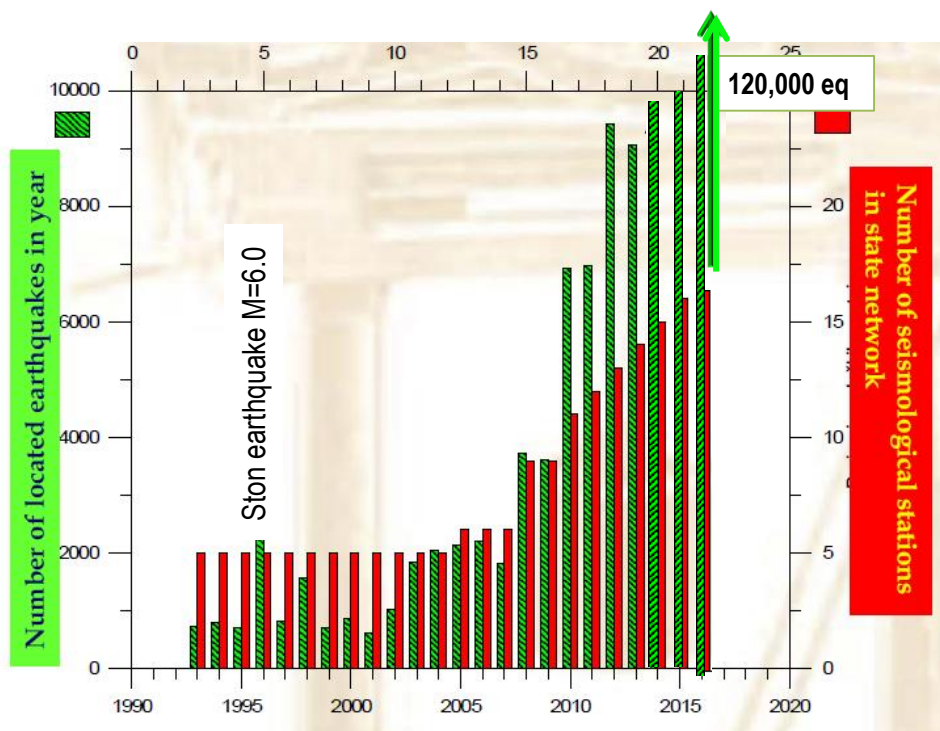Data broadcasting to Zagreb (ZAG) and Puntijarka (PTJ)

CARNET	(7)
DSL	(4)
GSM	(9)
SAT	(8)

CARNET (Croatian Academic and Research Network)
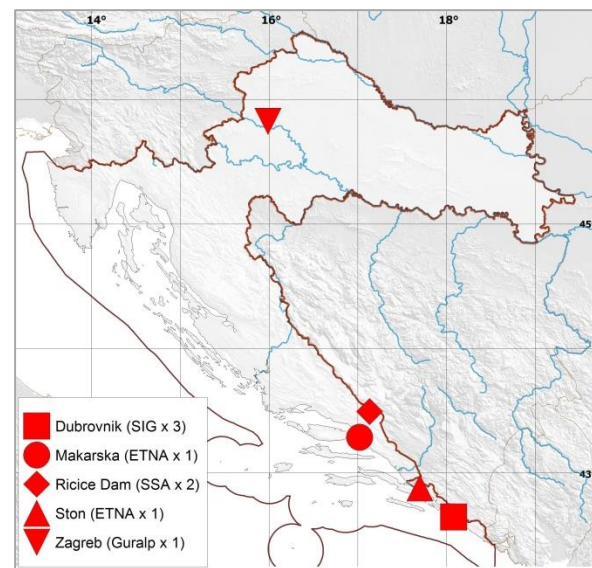
Croatian seismograph network

Seismograph network:

In the last 15 years:

- Number of stations × 3
- Located earthquakes × 12
- (Stuff is reduced from 8 to 6)

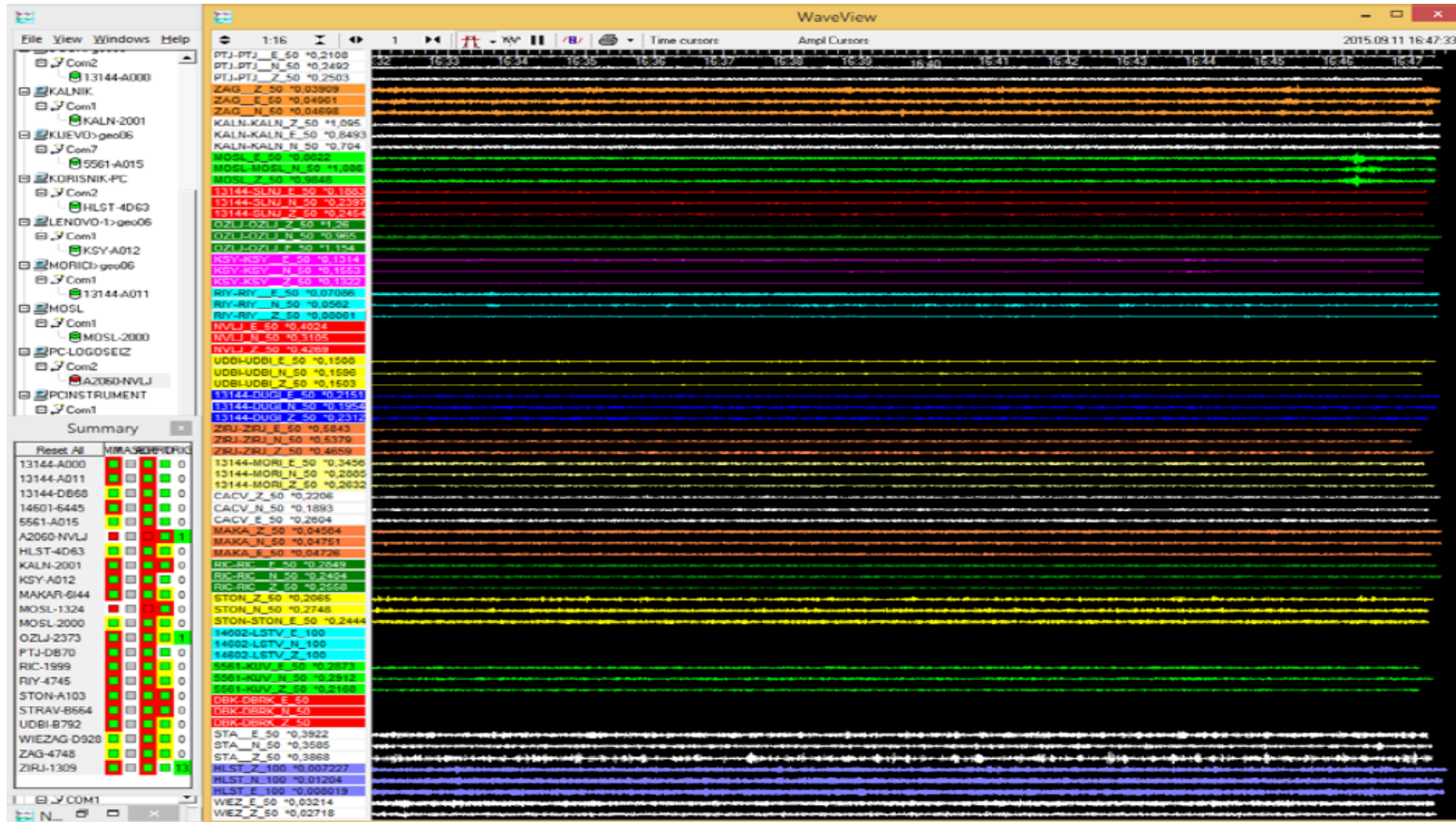## Strong motion network:

- 2019 - only 11 digital instruments are active today:
  - Dubrovnik (SIG) × 3
  - Makarska (ETNA) × 1
  - Ričice Dam (SSA-2) × 2 (temporary)
  - Ston (ETNA) × 1
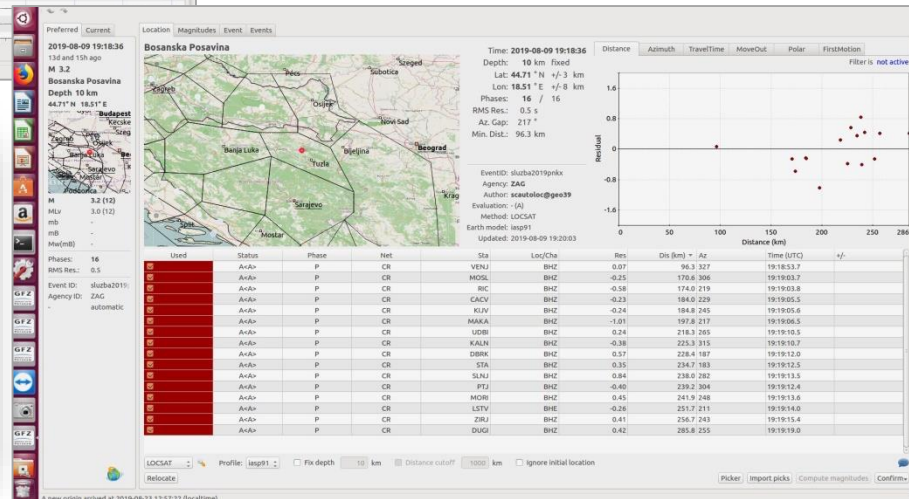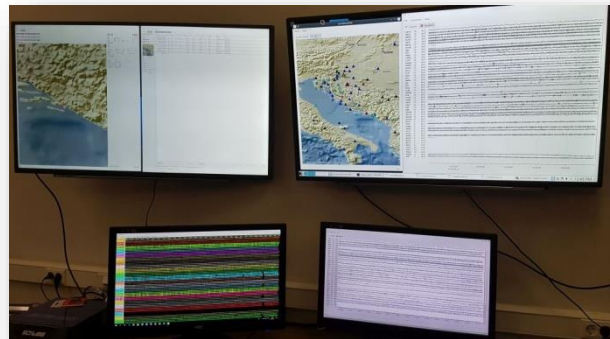 - Zagreb (Guralp) × 4

Croatian seismograph network

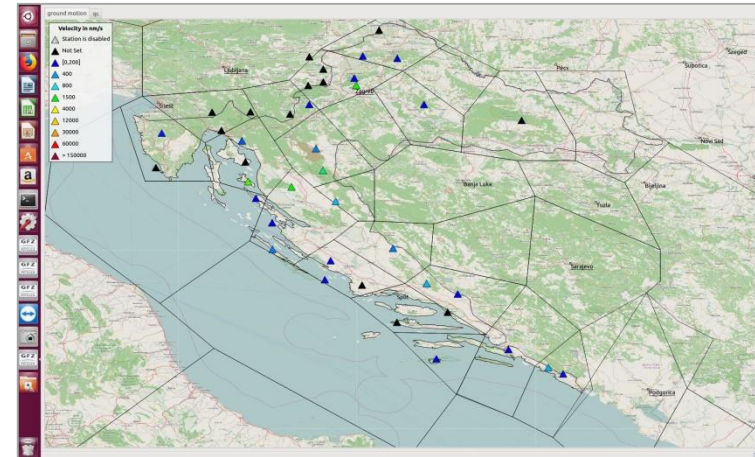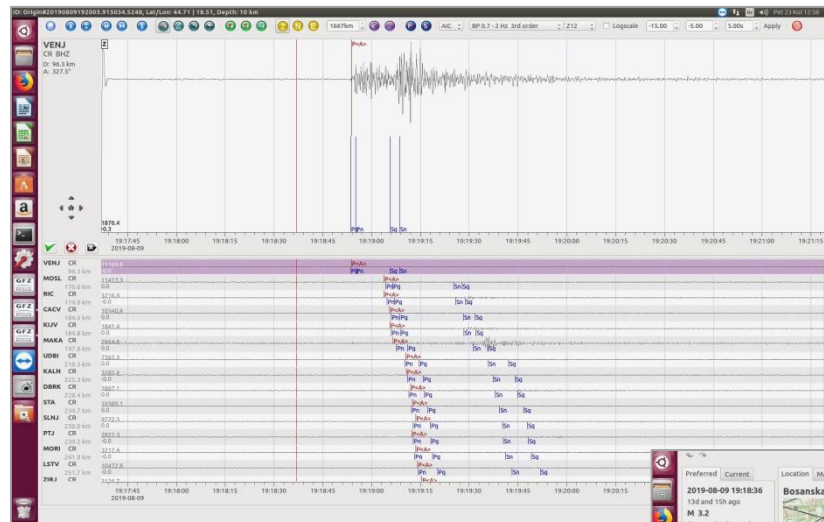Acquisition: Guralp – SCREAM *.gcf – format
(**S**eismometer **C**onfiguration, **RE**al-time **A**cquisition and **M**onitoring)

# Croatian seismograph network

Acquisition:

SeisComp – for automatic event detection and location

Croatian seismograph network

Software: SANDI – Seismological Analysis and Display
(developed in Geophysical Institute – Zagreb)

The earthquake hypocentral coordinates and origin times are calculated by the latest version of the HYPOSEARCH program based on a grid-search algorithm (Herak, 1989)
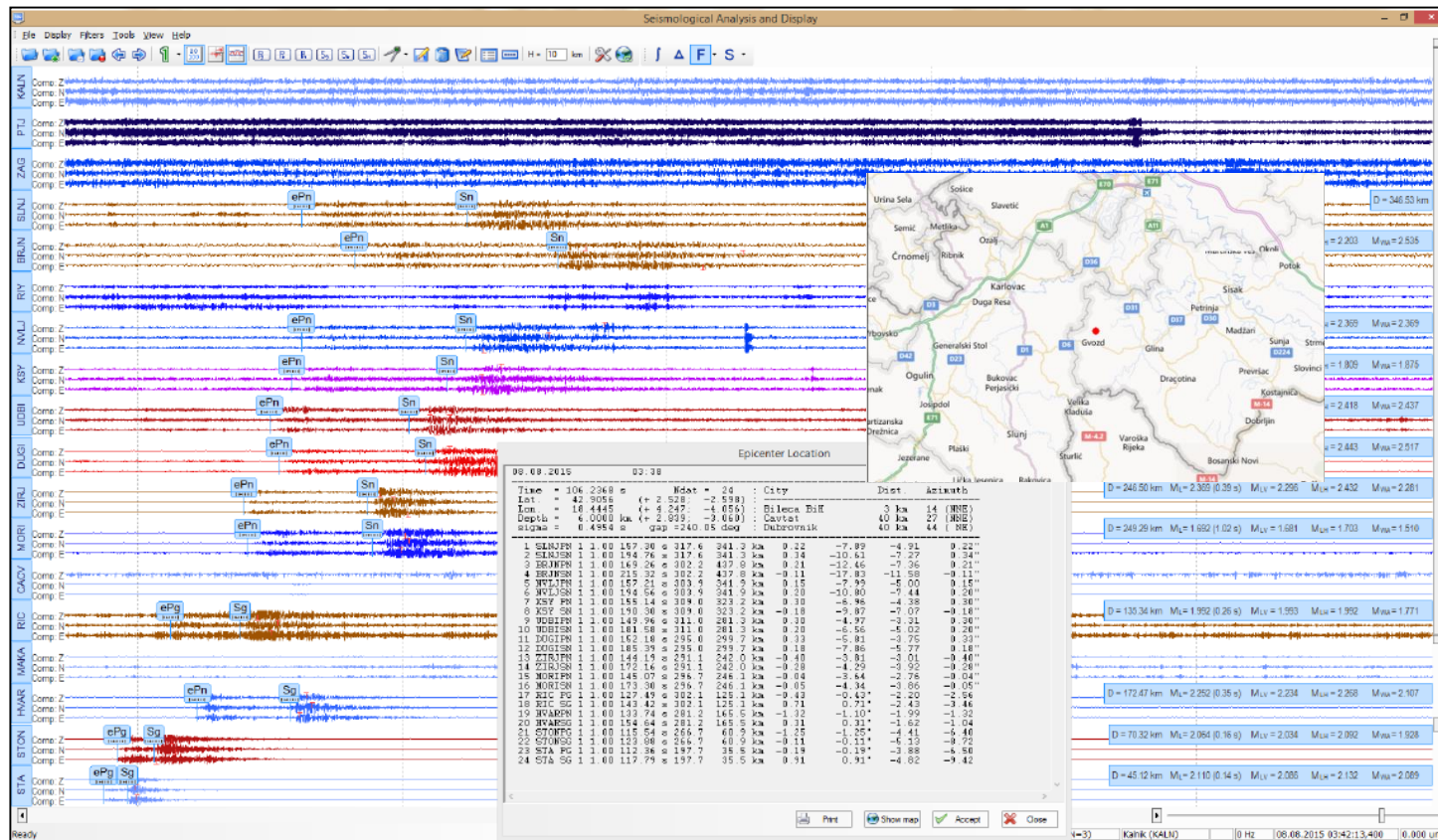
Croatian Seismological Database

Accumulation of all kinds of seismicity-related data:

- The historical earthquake database (documented earthquake information) lists about 200 earthquakes in Croatia before the instrumental era

- Macroseismic data (> 400 events) and maps archive

- Instrumental earthquake records (> 170 000 events)

- Fault-plane solutions (> 300)

- Phase readings for all analysed earthquakes (over 2 500 000 phase readings)

- Digital seismograms

- Strong-motion data

- Stations characteristics

    . . .

relational database

Croatian Seismological Database

Croatian Seismological Database (CROSEISDB) -

- integrates data from different sources and files into a single database
- enable multidimensional view of the data
- in-depth data analysis
- data visualization

CROSEISDB is the basis for determining the seismicity of Croatia

- statistical analysis of seismicity
- seismic hazard assessment
- macroseismic research
- making seismic hazard maps
- studies of the vulnerability assessment of individual buildings…

The historical earthquake database

- Data for almost 400 earthquakes

- More than 14,000 earthquake intensity data for each location where the earthquake was felt

Seismological Archive:

- historical data, questionnaires, isoseismal maps, photographs, drawings
- Historical Earthquake Information - various archives or specialized studies by other authors
- Balkan Area Seismic Research - Balkan Catalog – UNDP / UNESCO project
- Exchange of information with neighboring countries (Slovenia, Hungary...)
- Digital database - since 1995
- ...
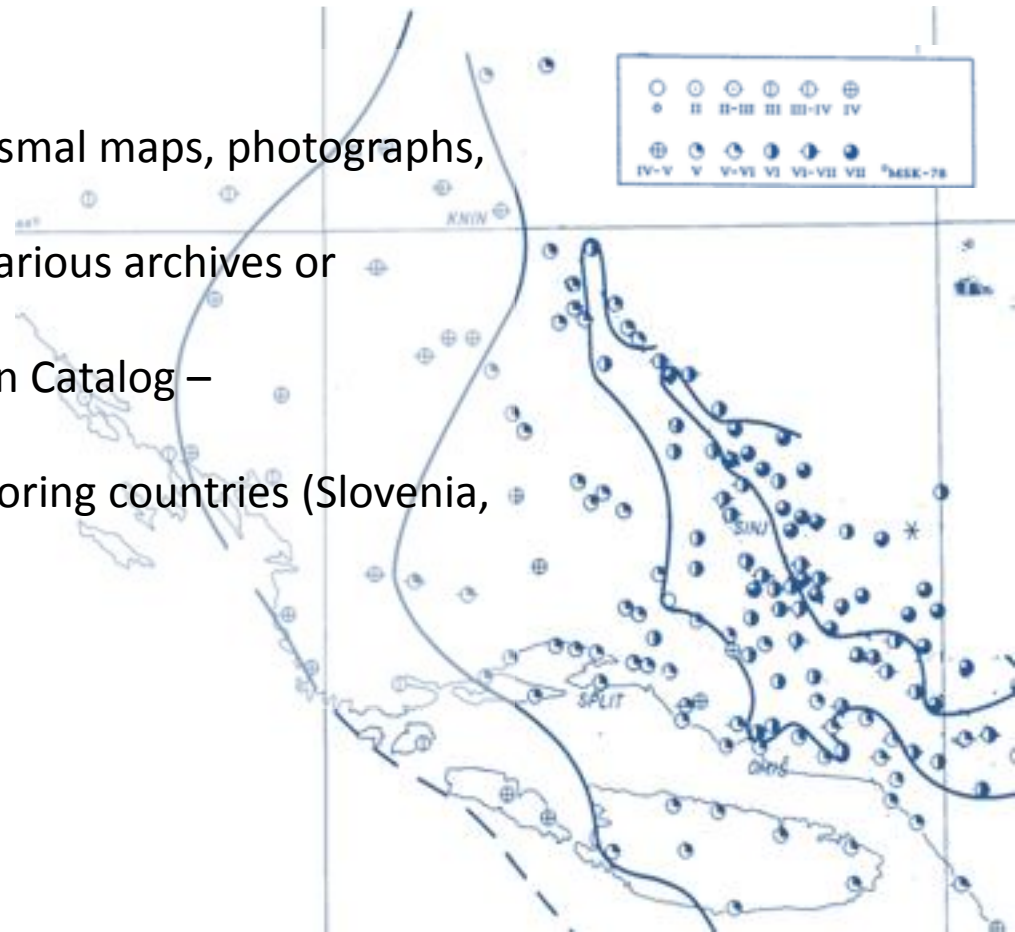
Croatian earthquake catalog (CEC)

Croatian Earthquake Catalogue

- BC – 2021
- Over 170.000 earthquakes
- Current rate of inclusion of events into the catalogue is about 12.000 eqs./year

Most intense seismicity:
- NW Croatia
- Greater Rijeka area (NW coastal region)
- Dalmatia (especially in the greater Dubrovnik area)
- Central Adriatic Sea

Low seismicity regions:
- Istria
- Slavonia (except the Slavonian Mts.)
- Lika
- Mt. Velebit
- Northern Adriatic Sea
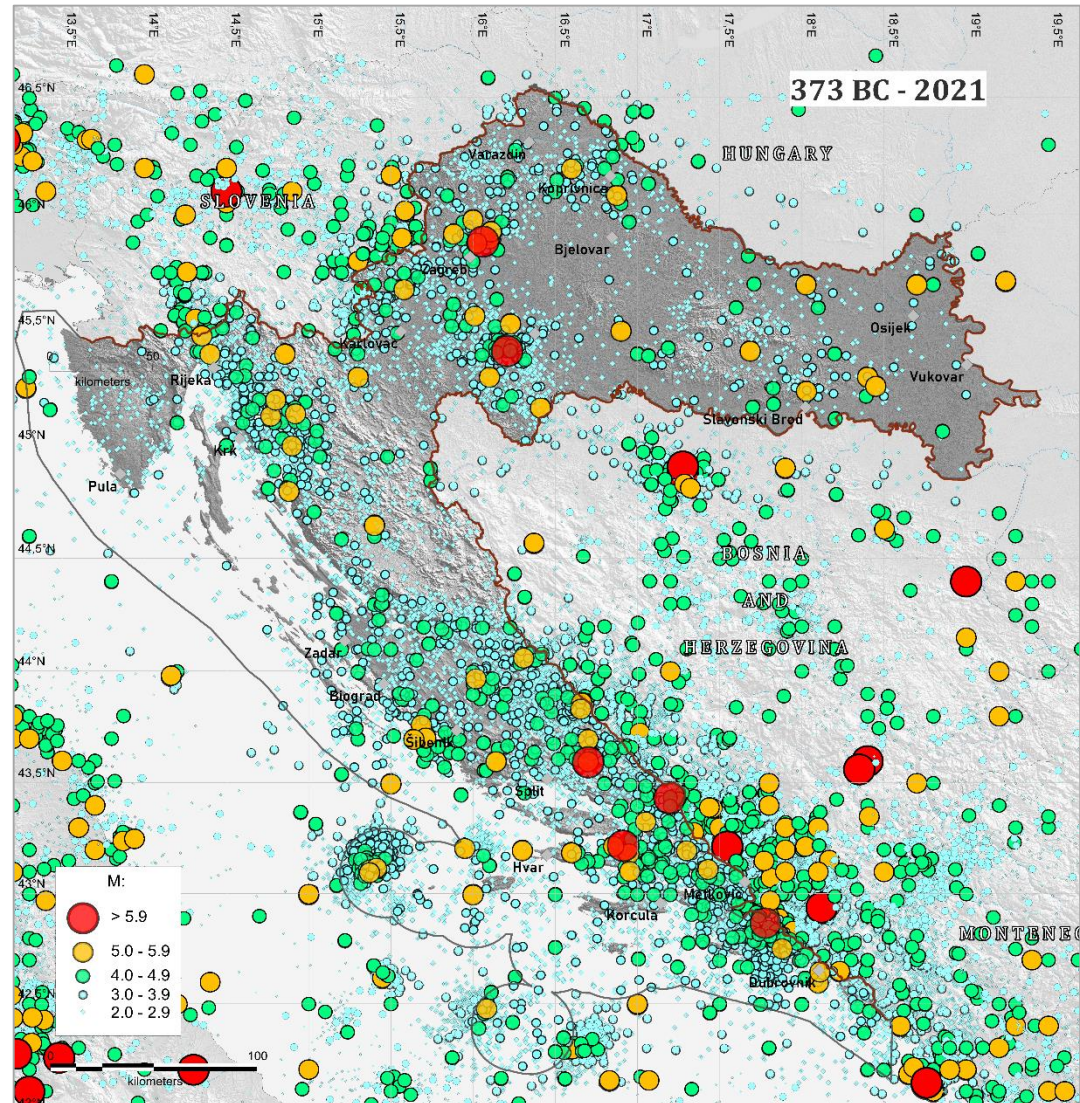
Croatian earthquake catalog (CEC)

- The CEC has been compiled using all data on earthquakes from the archives of the Department of Geophysics, Faculty of Science, University of Zagreb (the catalogues, macroseismic reports, seismograms, and other related documents…)

- hypocentral locations and magnitudes are obtained through location procedure using all data from Croatian stations as well as those reported by other regional networks

- In addition to the information on where and when an earthquake took place (epicentre coordinates and epicentral time), its focal depth, magnitudes and epicentral intensity, the catalogue contains the data on the location reliability, number of data used and references for each entry.

- The catalogue is routinely updated

Herak, M., Herak, D. and Markusic, S. (1996): Revision of the earthquake catalogue and seismicity of Croatia, 1908-1992 // *Terra nova*

…

Ivančić, I., Herak, D., Markušić, S., Sović, I., Herak, M. (2002): Seismicity of Croatia in the period 1997-2001. // Geofizika,

Ivančić, I., Herak, D., Markušić, S., Sović, I., Herak, M.(2005): Seismicity of Croatia in the period 2002-2005. // Geofizika

Ivančić, I., Herak, D., Herak, M., Allegretti, I., Fiket, T. Kuk, K., Markušić, S., Prevolnik, S., Sović, I., Dasović, I., Stipčević, J. (2018): Seismicity of Croatia in the period 2006–2015. // Geofizika
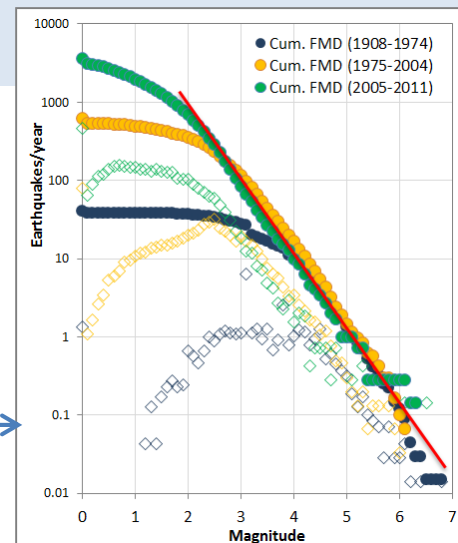
Croatian earthquake catalog (CEC)

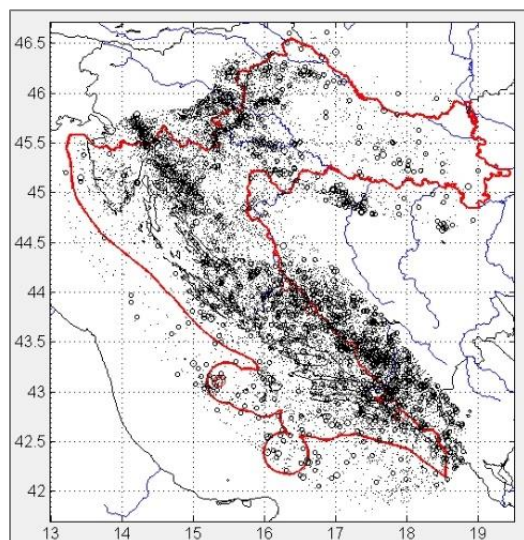## The completeness thresholds (M_c) of CEC
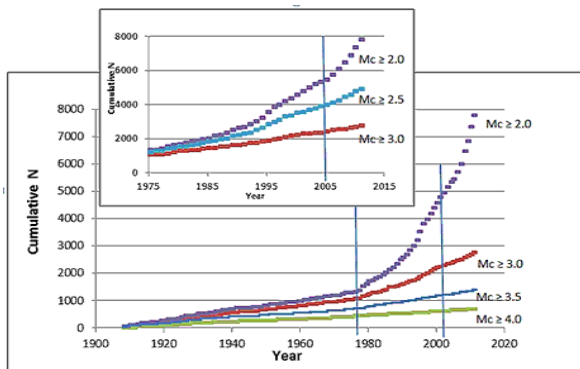
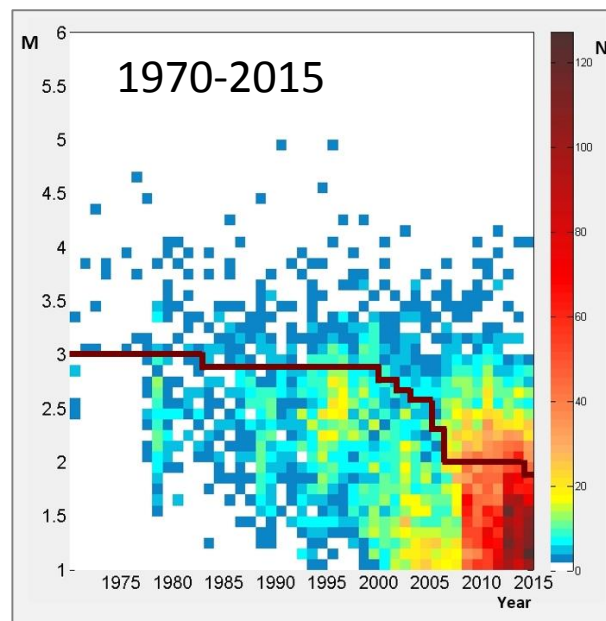Time distribution of seismic events (mainshocks) by year, ($M_L \geq 2.0$)

1908-1974: $M_C \geq 4.0$, ($b_{ML} = -0.86$);
1975-2005: $M_C \geq 3.0$, ($b_{ML} = -0.94$);
2006-2015: $M_C \geq 1.9$, ($b_{ML} = -0.90$);
(max.-likelihood b-value, after
Gutenberg-Richter relationship)

Frequency-magnitude distribution

1970-2015

Magnitude distribution timeline

Yearly number of mainshocks in the period 1970–2015, within bins 0.1 magnitude units wide is given by the colour scale. The thick line is the step-plot presentation of completeness thresholds (M_c)

Map of mainshock epicentres in Croatia and the surrounding areas in the period 1970–2015

Ivančić, I., Herak, D., Herak, M., Allegretti, I., Fiket, T. Kuk, K., Markušić, S., Prevolnik, S., Sović, I., Dasović, I., Stipčević, J. (2018): Seismicity of Croatia in the period 2006–2015, Geofizika

Seismicity of Croatia

The strongest earthquakes in Croatia

City	Date	Magnitude (M_l)	Intensity (°MCS)
Dubrovnik	6 April 1667	7.0*	IX-X
Ston	13 April 1850	6.4*	VIII-IX
Zagreb	9 November 1880	6.2*	VIII
Trilj	2 July 1898	6.7*	IX
Pokuplje	8 October 1909	5.8	VIII
Vinodol	12 March 1916	5.8	VIII
Novigrad Podravski	27 March 1938	5.6	VIII
Imotski	29 December 1942	6.2	VIII-IX
Makarska	11 January 1962	6.1	VIII-IX
Dilj Gora	13 Aprilj 1964	5.7	VIII
Ston-Slano	5 September 1996	6.0	VIII
Zagreb	22 March 2020	5.5	VII
Petrinja	29 December 2020	6.2	VIII

Magnitude	Number of eartquakes per year (since 1970)
M ≥ 6.0	0.06 (since1800)
M ≥ 5.0	0.6
M ≥ 4.0	6.9
M ≥ 3.0	55
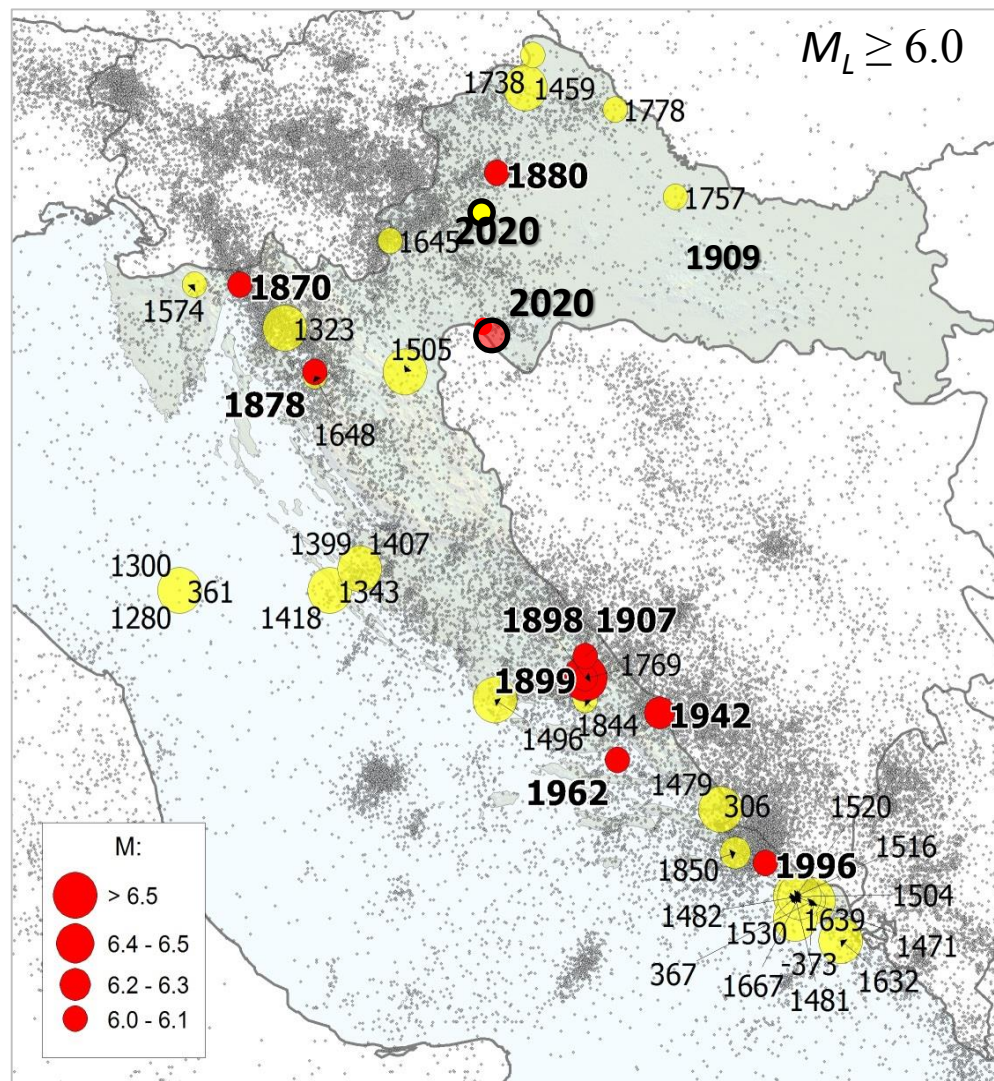
Red dots: events after 1850
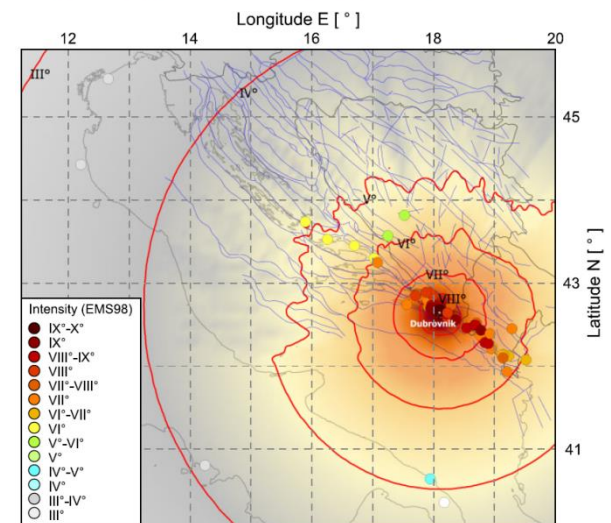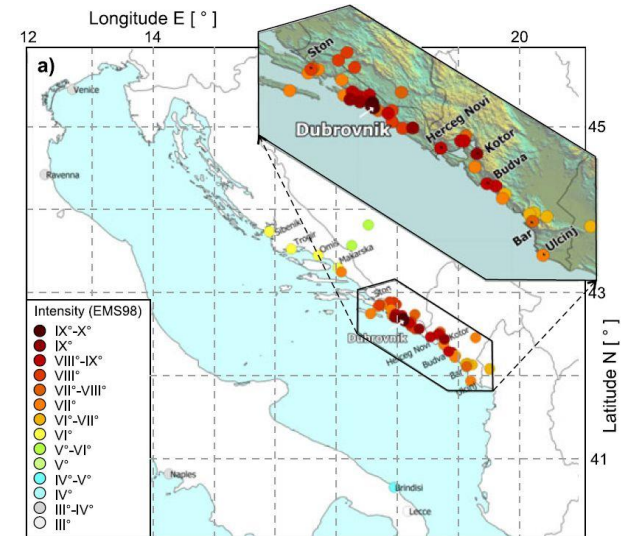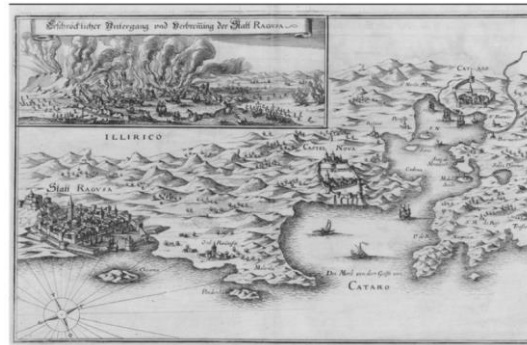Yellow dots: 373BC - 1850

Seismicity of Croatia

*The great **1667 Dubrovnik earthquake** caused extensive damage in a wide area around this old Dalmatian town (today in Croatia).*

I_{max} = IX-X EMS98

M_w = 7.06

City lost almost half of its population. The earthquake and a persistent fire that followed reduced Dubrovnik to an unrecognizable pile of burning rubbles surrounded by the city walls which almost miraculously remained intact.
This earthquake destroyed or damaged most of the houses from Dubrovnik to Budva.

- The 1667 Dubrovnik earthquake is the strongest documented earthquake in the coastal part of Croatia, since it significantly affects the seismicity and seismic hazard assessment.

(Markušić, I Ivančić, I Sović (2016): The 1667 Dubrovnik earthquake–some new insights// Studia geophysica et geodaetica 61)
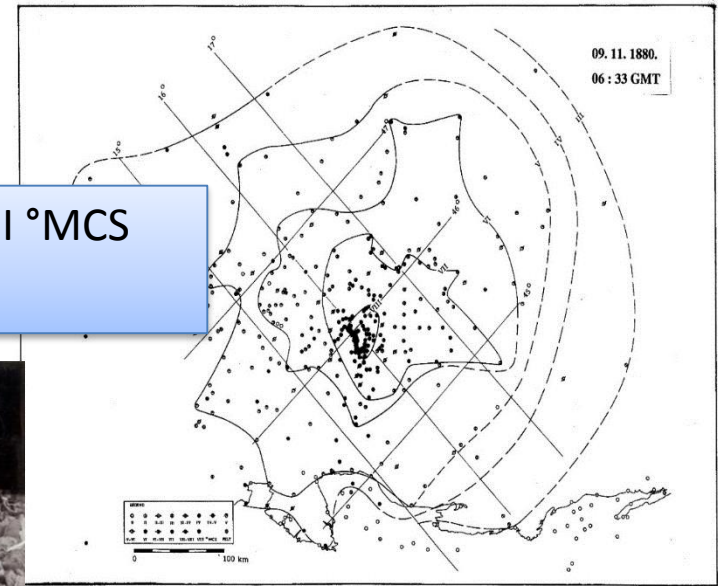
Seismicity of Croatia

- The **Zagreb Earthquake** occurred on **November 9, 1880 at 07h 34m UTC** near Kašina, and is often referred to as the "Great Zagreb Earthquake".

All of the 3670 buildings (Zagreb had about 30,000 inhabitants at the time) were damaged and about 13% were destroyed. One person was killed and 29 were seriously injured.
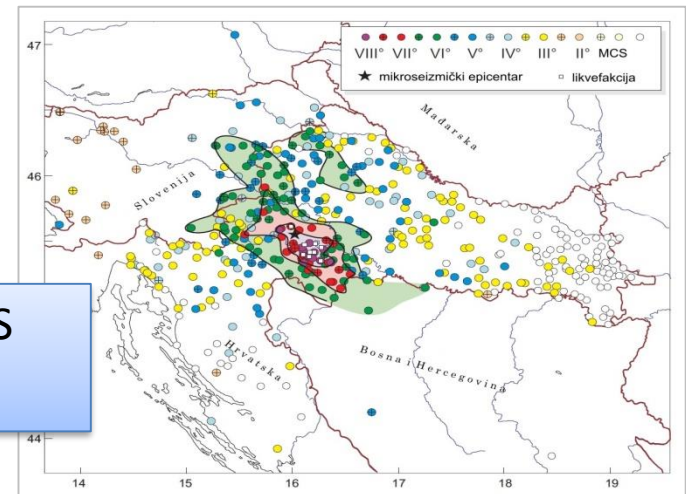

I_{max} = VIII °MCS
M = 6.2

- The ***Pokupsko earthquake*** is among the most famous earthquakes, not only in Croatia but globally. The earthquake occurred on **October 8, 1909 at 10h 59m UTC**, with the epicenter 9 km north of Pokupsko.

A major earthquake was followed by more than 50 aftershocks

I_{max} = VIII °MCS
M = 5.8

Seismicity of Croatia

- The ***Ston-Slano earthquake sequence*** (main shock **5 September 1996**) completely destroyed three villages, and caused heavy damage in a number of southern Dalmatian cities. It is the largest seismic series in the greater Dubrovnik area since the catastrophic 1667 Dubrovnik earthquake.

- The main shock was followed by thousands of aftershocks.
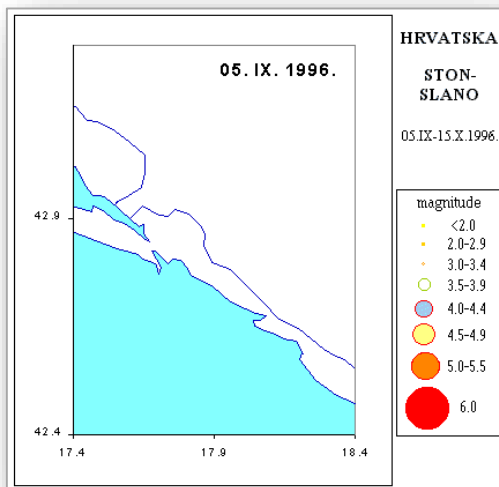
I_{max} = VIII °MCS

M = 6.0

Zagreb

22 March 2020 . 06:24
M_L = 5.5
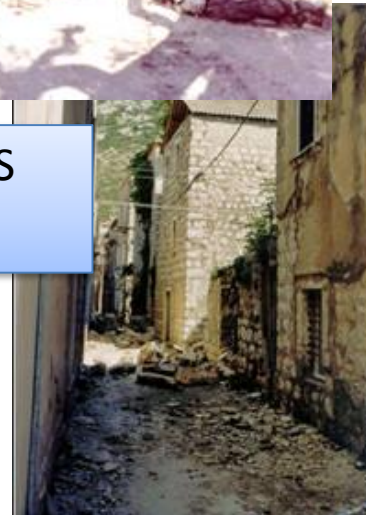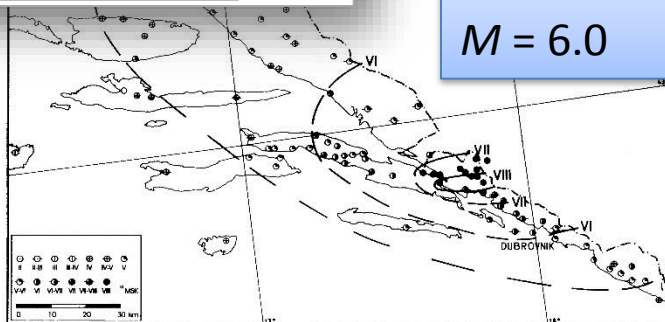
Petrinja

29. December 2020. 12:29
M_L = 6.2 (Mw=6.4)

IZVOR: RDNA, March 2020:

Photo: Damjan Tadić / CROPIX
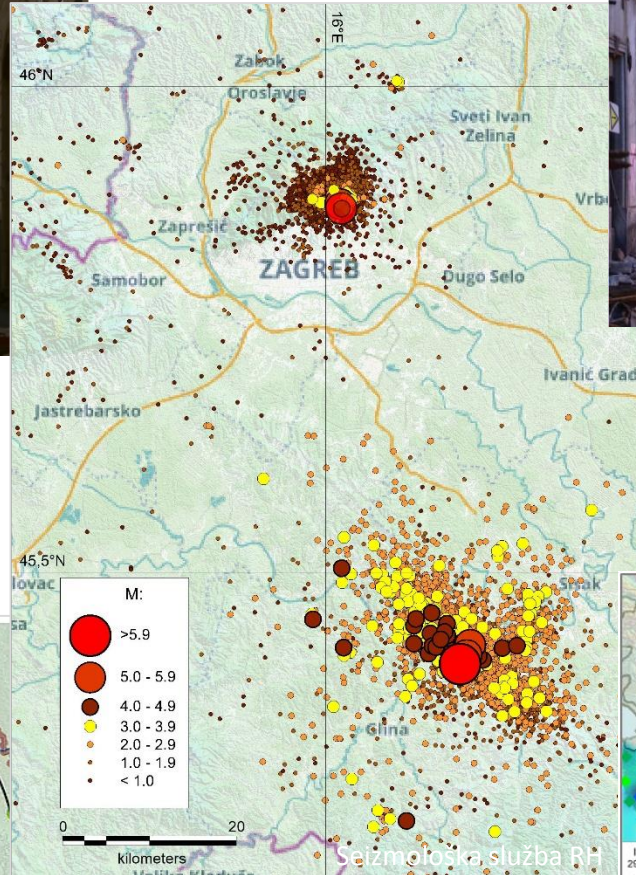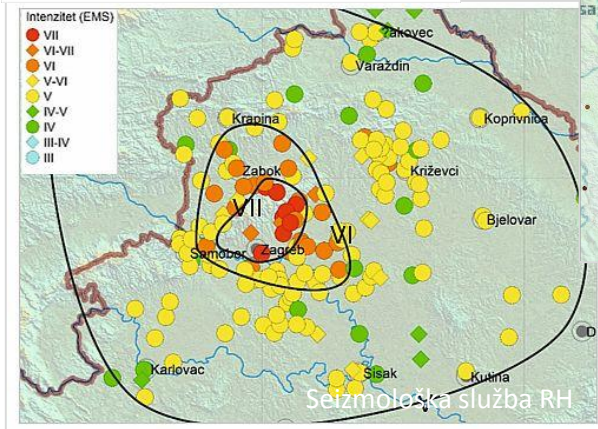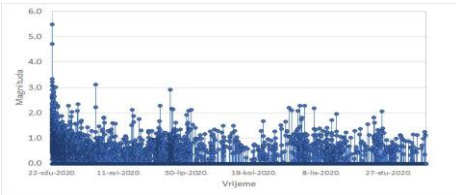
© Božidar Vukičević | Cropix

IZVOR: RDNA, Dezember 2020 :

18700 aftershocks recorded.

Intenzitet (EMS)
- VII
- VI-VII
- VI
- V-VI
- V
- IV-V
- IV
- III-IV
- III

Seizmološka služba RH

M:
- >5.9
- 5.0 - 5.9
- 4.0 - 4.9
- 3.0 - 3.9
- 2.0 - 2.9
- 1.0 - 1.9
- < 1.0

kilometers

Seizmološka služba RH

KARTA IZOSEISTA (EMS)
29.12.2020.
11:19 (UTC) M=6.2

Intenzitet (EMS)
29.12.2020. 11:19 (UTC)
- VIII
- VII-VIII
- VII
- VI-VII
- VI
- V-VI
- V
- IV-V
- IV
- III-IV
- III
- II-III
- II

Seizmološka služba RH
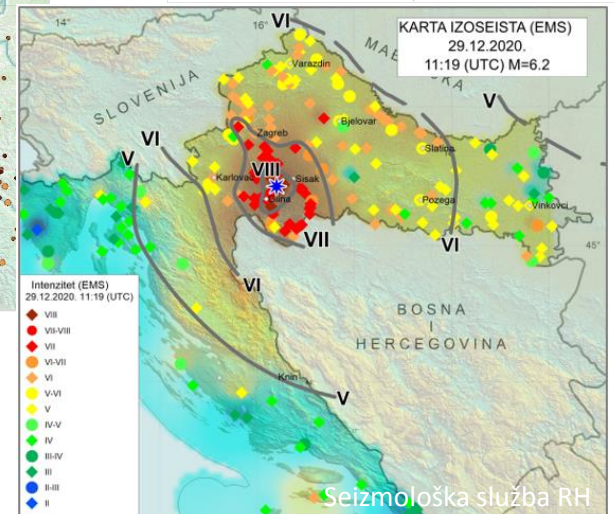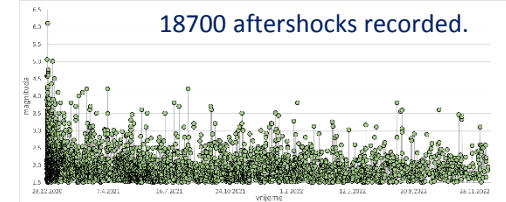
Zagreb
22 March 2020 . 06:24
M_L = 5.5

- **The epicentre was at Markuševec, 7 km north of the centre of Zagreb, at a depth of only 8 km.**

- The March 2020 earthquake resulted in one fatality, 26 injuries, and the displacement of thousands of people.

- In the aftermath of the earthquake, 488 people were housed in an evacuation centre, and an unknown number took shelter with friends and relatives.

- The earthquake resulted in damage to about 26,000 buildings in the City of Zagreb, Krapina-Zagorje County and Zagreb County.

- The impact of the disaster on Zagreb's historical center is one of the main reasons for the very high cost of earthquake damage.

Petrinja
29. December 2020. 12:29
M_L = 6.2 (Mw=6.4)

- **Sisak-Moslavina County in Croatia, the epicenter was 6 km outside the town of Petrinja**.

- The earthquake was preceded by a **5.0 magnitude earthquake on December 28, 2020**; and numerous aftershocks were recorded, including a **5.0 magnitude earthquake on January 6, 2021**.

- Seven people died, 15 sustained severe injuries that required hospitalization, and dozens more suffered minor injuries due to the December 29, 2020, earthquake.

- approximately 43,000 buildings were reported as damaged; and close to 25,000 of these have been inspected for usability by the civil engineers.

- The earthquake affected the provision of public services and economic activities, with damage and loss of assets deeply disrupting livelihoods of thousands of people living across multiple counties.

Photo: Damjan Tadic / CROPIX

The extent of the damage in Zagreb and its surroundings and in Banovina is estimated at around EUR 17 billion which EUR 11.5 billion relates to Zagreb and the surrounding area, and EUR 5.5 billion to Banovina

29 December 2020

(a) Gora, (b) Letovanić, (c) Strašnik,

Kravarsko

Majske
Poljane

Dropout dolines

liquefaction

Several geological processes, including liquefaction, severely affected the natural environment and land stability of the area

Croatian Seismological Survey
practice & science

PROFESSIONAL WORK:

- establishment, maintenance and development of seismograph network in Croatia , data analyses, archiving digital data, performing macroseismic field work and analyses; bulletins, data exchange, cataloguing …
Collaborations and data exchange: CSEM, ORFEUS, CE^{3}RN, AdriaArray

- All aspects of Croatian seismicity (location and quantification of earthquakes, FPS…), studies of the structure and properties of the Earth's interior – mostly crust and upper mantle, attenuation and anisotropy, engineering seismology, PSHA, vulnerability of buildings, …

Collaborations:

Univ. Hamburg, Univ. Trieste, USC-LA, ETH Zürich …

Projects:

AlpArray, CASE, Velebit, HOLISTIC, NATO x 3, GSHAP, MIDSEA, COST, COPERNICUS, EUROSEISMOS, AdriaArray …

Seismic station Kalnik

Seismic station Lastovo

Thank you!