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Development of Seismometry and Seismic Tomography in Croatia

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编者按：克罗地亚地球物理学家莫霍洛维奇在研究 1909 年 10 月 8 日克罗地亚地震的地震波走时特征时，首次发现了该地区的地壳与地幔的分界面，后被命名“莫霍界面”，简称 Moho 界面。1927 年，莫霍洛维奇又在地震记录中识别出了 S*震相，证实了在地壳内部还会存在另一个康拉德（Conrad）间断面。地震层析成像是研究地球内部结构的重要方法之一。为纪念莫霍洛维奇诞生 150 周年，莫霍界面发现 100 周年，特发此文，以兹纪念。

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Dedicated to Andrija Mohorovičić, the greatest Croatian scientist and one of the founding fathers of seismology, on the occasion of the 150th anniversary of his birth.

“... The goal of seismology is to study the interior of the Earth, and to continue where the geologist stops; it has in modern seismographs a sort of binoculars that enables us to look into the largest of depths...”. These sentences, written down by Andrija Mohorovičić as early as 1913, perfectly depict the essential role that seismology has in unveiling the secrets of the Earth’s interior. Indeed, a huge portion of what we know today about the constitution of the deepest as well as of the more shallow parts of the inside of our planet comes from interpretation of seismological data. Being an inverse problem par excellence, contemporary seismic traveltime and waveform tomography relies on high quality seismograms collected by seismographs deployed all over the world. In fact, one may state that tomographic methods in geophysics were just waiting for the instruments to evolve to the level to be able to produce usable data.

1　Early days of seismometry

1.1　Seismoscopes, seismometers and seismographs

Although the first known instrument for observing earthquake-induced ground motion – the famous Chang-Hêng seismoscope – was constructed in China in 132 AD, the discipline of seismometry has started its rapid development in 18th century Europe. At that time, the favourable cultural climate and prevalence of Cartesian philosophy which promoted the idea that the art of measurement can become the research object itself, independent of any particular object of study, provided fertile environment for methodological and practical advancement of construction of seismological instruments. As it often happens in seismology, intense seismicity in parts of Europe also boosted efforts there to make instrumental observations of the phenomenon. The early years of seismometry were described by a number of authors, but the paper of Dewey and Byerly (1969) stands out among them. Two hundred years of seismic instrumentation in Italy are

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beautifully presented in a monograph edited by Ferrari (1992). This short review relies heavily on material presented therein.

The first written document dealing with a construction of an earthquake sensing device in Europe dates to 1703, when French abbé Jean de la Haute-Feuille described his mercury seismoscope. It consisted of a wide bowl filled with mercury to the brim, under which there were eight containers arranged in circle at equal distance one from another. During an earthquake the mercury would spill over, and the observer could get the idea of severity of shaking and about the direction towards the epicentre by noting the amount of mercury spilled, and by observing the azimuth of non-empty containers. De la Haute-Feuille also wrote about the need of a large number of instrumental observations before attempting any earthquake prediction. There is no evidence that his seismoscope was ever actually constructed, but the idea survived and similar instruments were later built in Italy (e.g. Cavalli in 1784). A number of seismoscopes – devices for recording earthquake shaking with no time axis – were constructed during the 18th and the first half of the 19th century. Notable among them are the instruments by Cirillo (1731), Bina (1751), Zupo (1783), Salsano (1783), Cavalli (1784, 1785), Cacciatore (1818, Fig. 1), Pagani (1834, 1841), Cavalleri (1858). Most of them used some kind of a pendulum or employed a variant of de le Haute-Feuill’s construction. Cavalleri proposed to use a mass on a spiral spring to detect vertical motion. He also realized that seismic waves cover a wide spectrum and constructed a seismoscope with six different pendulums in 1860. Models from the mid-19th century, often featured a time-telling device that recorded the onset time of shaking (e.g. Palmieri’s 1856 sismografo elettro-magnetico, an elaborate setup of different seismoscopes and clocks, Fig. 1). Those seismoscopes recorded many earthquakes in Calabria and Naples. Besides Italy, seismoscopes were also being constructed in Scotland (Forbes’s seismometer in 1844 utilizing the inverted pendulum for the first time, accompanied also with a mathematical theory of the instrument), and in England (Mallet, in 1851). Most of these instruments were used only locally by their inventors, but some of them were operational in various parts of the world (e.g. Palmieri’s sismografo in Tokyo and California). In the 1880-ies horizontal pendulums were proposed by several authors, most notable of which is probably Zöllner whose design of 1869 was later used in Galitzin and Wood-Anderson seismographs.

Figure 1. *Left*: The Cacciatore mercury seismoscope, 1818; *Right*: The Palmieri electromagnetic seismograph (sensors part), 1856. After Ferrari (1992).

The first “true” seismograph – according to Agamennone (1906) – was built in Italy in 1875 by F. Cecchi. The apparatus incorporated two common pendulums for horizontal motions, a mass on a spring sensitive to vertical oscillations, and even a sensor for rotational motions. Cecchi installed a triggering device that started the motion of a recording surface when an earthquake was detected, thus probably producing the first time-history of earthquake waves.

However, the first preserved recording of an earthquake made on Cecchi's instrument is the one from February 1887, which is seven years after the first seismogram was recorded by British scientists in Japan, among which J. Milne, J. Ewing and T. Gray are principal figures. They used their instruments to study the propagation of seismic waves, in large part for the engineering purposes, and thus paved the way to use seismographs as practical research instruments. Ewing's first seismograph, built in 1879, used a common pendulum and motions of the styluses were recorded on a circular smoked glass plate. Soon afterwards J. Ewing changed the design using a horizontal pendulum (the "garden-gate" suspension), which enabled construction of longer period instruments. This feature was shared by most of the instruments built by British professors in Japan. The problem of choosing the period of free oscillations was, surprisingly, only seldom considered important. Some, like J. Ewing, advocated periods longer than those of earthquake waves, whereas others (*e.g.* Perry and Ayrton, 1879) preferred very short-period seismographs, essentially accelerographs. Damping was also little debated, and Ewing (1883) even recommends virtually undamped systems. Perry and Ayrton (1879) suggest viscous damping, whereas Milne and Gray use friction to damp their instruments.

Ewing's seismograph recorded the first 'complete' seismogram of a local Japanese earthquake on November 3, 1880. Gray and Ewing constructed a vertical seismograph in 1882.

At the same time, in Italy, developments in Japan were followed and analysed, but common-pendulum design is the preferred one (*e.g.* Brassart's pendulum, modified later with Agamennone, or Cancani's instrument with 7 m long pendulum). All these instruments used mechanical recorders and suffered from excess friction thus requiring large masses.

The first known seismogram of a distant earthquake was obtained by E. von Rebeur-Paschwitz in 1889, who recorded in Potsdam a large event in Japan (Fig. 2). The instrument, consisting of small horizontal pendulums was constructed for astronomical purposes, to measure small changes in the direction of the vertical. Von Rebeur-Paschwitz was the first to use photographic recording for continuous seismological measurements. The instrument was later improved by R. Ehlert.

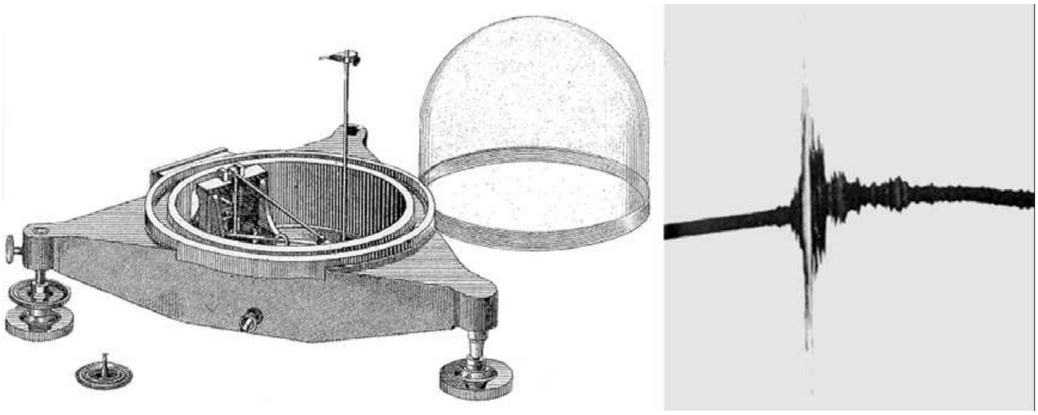

Figure 2. *Left:* Instrument by E. von Rebeur-Paschwitz which recorded in Potsdam, Germany, the first teleseismic earthquake on April 17, 1889 with the epicentre in Japan. Seismogram is shown on the right.

In 1895 Vicentini and Pacher presented the *Vicentini microsismografo* with a common, undamped pendulum with a mass of 100 kg, achieving magnification of about 80. It recorded two horizontal components on smoked paper alongside with the trace with time marks. Later they also introduced a vertical seismometer using a leafspring design. In Japan, after Milne and his colleagues returned to Britain, F. Omori took over and constructed a prototype of a later widely used Bosch-Omori instrument.

In Göttingen (Germany), E. Wiechert presented in 1898 the first seismograph with a viscously damped pendulum. Soon afterwards, after visiting Italian scientists, Wiechert constructed in 1900 his famous instrument based on the inverted pendulum design, with piston-cylinder devices for damping, which could easily be adjusted and calibrated. The instrument was installed in Göttingen in 1903 after some modifications and improvements. The pendulum mass was 1000 kg, which enabled static magnification of about 200 (Fig. 3). Recording was mechanical on a smoked paper, and time marks were provided by lifting the styluses off the paper every minute. This seismograph, together with Wiechert's later constructions (80-kg instrument, vertical component seismograph, 17-ton seismometer...) provided seismologists with instruments capable of accurate recording of ground motion during local as well as distant earthquakes. Wiechert instruments served as basic observatory seismographs on many stations world-wide even in the second half of the 20th century.

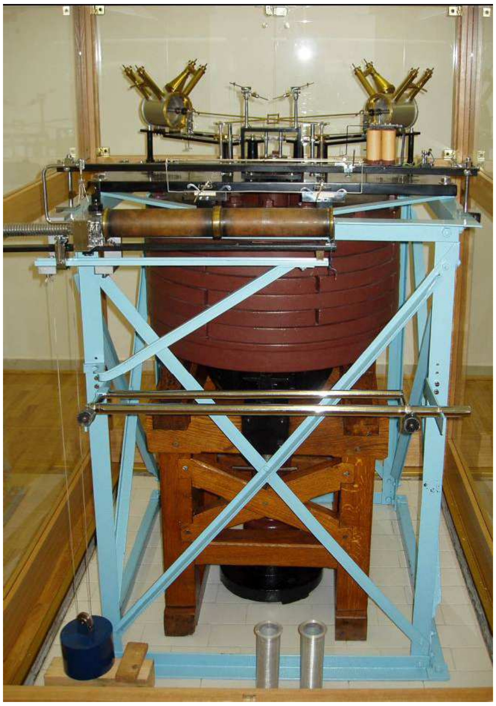

Figure 3. Wiechert horizontal seismograph (1000 kg) which Mohorovičić installed in Zagreb in 1909. A few months later the instrument recorded the famous Kupa Valley earthquake of October 8. Today it is exhibited in the A. Mohorovičić Memorial Rooms, restored and in perfect operating conditions.

Let us conclude this short overview of the birth of a modern seismograph with the electromagnetic moving-coil instrument with galvanometric three-component recording on photographic paper featuring electromagnetic damping, constructed by the Russian B. B. Galitzin in 1905. Due to virtual absence of friction, the instruments proved to be very effective, and achieved high sensitivity and amplification. This innovative design eventually prevailed and electromagnetic instruments gradually replaced mechanical seismographs.

1.2 Timing

Even a perfect seismograph is virtually useless – especially for any kind of tomographic study – unless it incorporates a quality absolute timing device. If one is going to use arrival times of seismic phases to infer the properties of the medium through which they are transmitted, or to locate the position of earthquake hypocentre, an error of one second will map into the error of 6~8 km in space. Therefore, although good seismographs might have existed, and the theory could have been developed, widespread application of inverse methods had to wait until enough seismological stations were equipped with observatory clocks which were well kept and accurate enough. Citing Mohorovičić (1924) again:

"...A beautiful and comparable record of an earthquake has, however, almost no value if one is not in a position to assign to the beginning of an earthquake, or to its phases, the exact standard time. For the registration of earthquakes not only the records but also the times must be comparable... The first requirement in the setting up of a new station is the purchase of a first-class time clock, with an absolute guaranty of a permanent service furnishing the time to within at least 0.5 second. If this cannot be had it would be better to abandon the station rather than to lead the service into error through false time...”. The time errors of tens of seconds were not uncommon even for well kept seismological observatories in the first few decades of the 20th century. Keeping absolute timing was a difficult task, and could have been achieved only by very careful daily calibration of clocks against astronomical observations (e.g. the observation of passage of stars through the local meridian, Figure 4). The situation was much improved once time-signals became available by telegraphic and especially wireless transmissions after about 1910. Today we take accurate GPS timing for granted.

Figure 4. *Left:* Passage instrument by Eugen-Hammermüler used by Mohorovičić in the period 1892–1913 to daily observe the passage of stars through the local meridian on the Zagreb observatory. This absolute time was recorded by a chronograph, and used to calibrate the Riefler pendulum clock (*right*) which provided time signals for the Wiechert seismographs (exhibited in the A. Mohorovičić Memorial Rooms in Zagreb).

The time was recorded directly on seismograms, at first on a separate trace (like on the Vicentini seismographs), and later by brief interruption of recording at regular time intervals. The timing accuracy depended on how well the clocks providing timemarks were calibrated and how often their corrections were determined; the timing resolution depended on the speed (and its stability) of the recording paper. Taking all this into account, the accuracy and resolution achieved at the very beginning of the 20th century only exceptionally exceeded 0.5 s.

2 Inverse problems in Croatia

The first proper travel-time tomographic study for regional and local distances is, to the best of our knowledge, the one by Mohorovičić (1910a, b, c), which lead to the discovery of the crust-mantle boundary, subsequently named after him (often popularly known as the Moho). Analysing seismograms of the Croatian earthquake which occurred on October 8, 1909, he noticed that travel-times of recorded elastic waves indicate existence of up to then unknown seismic phases that could only be explained by assuming a refracting surface at the depth of about 54 km. To arrive at this conclusion, Mohorovičić had to assume the law of velocity increase with depth, and to set-up and solve the forward problem of elastic wave propagation in spherical model of the uppermost part of the Earth. He then used the trial-and-error method to adjust model parameters so that the theoretical travel-time curves closely matched the observed ones (Figure 5).

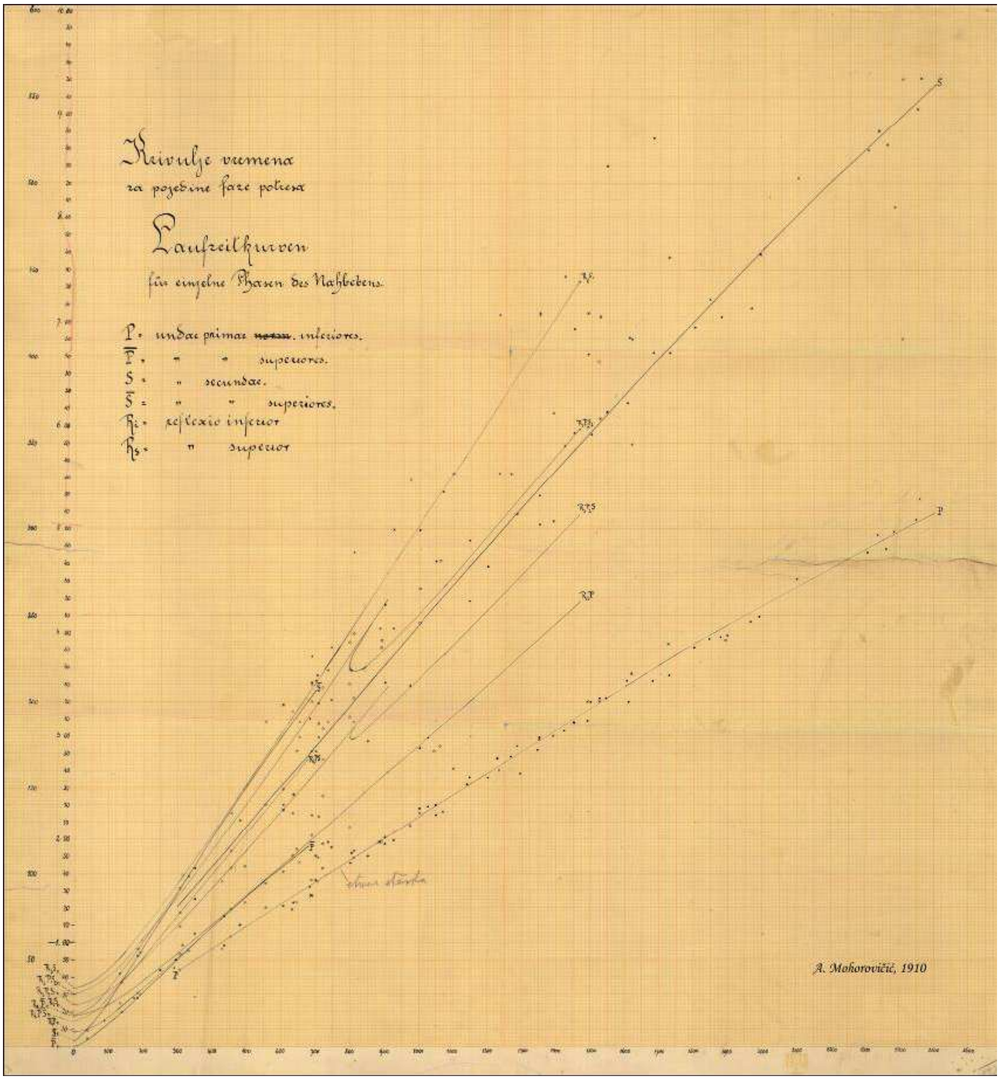

Figure 5. Mohorovičić's travel time curves for local and regional distances constructed in 1910. Observed onset times are marked with dots, full lines are the theoretical travel-time curves for individual (Pg, Sg) and normal (Pn, Sn) phases, as well as for the main crustal reflections for the best fitting model of the crust and the upper mantle.

After Mohorovičić's times, Croatian seismology suffered until recently from limited resources and chronic lack of instruments. Studies involving inverse problems – apart from industrial applications by the national petroleum company – were therefore limited to low-resolution investigations of velocities in the crust and upper mantle using onset times of various seismic phases reported by regional and local networks (*e.g.* Herak, 1990; Herak and Herak, 1995). Observed travel times of direct waves between foci within a well defined hypocentral volume were used by Lokmer and Herak (1999) to infer seismic velocity anisotropy in the External Dinarides. They applied a novel method involving summation of differential paths and travel times within a number of azimuthal windows. The results indicated excellent agreement of the direction of maximum tectonic compression with the one of the fast velocity, which is interpreted to be due to stress-alignment of microcracks in the surrounding rock volume.

The same conclusion has also been reached by Herak et al. (2003) who used the same algorithm to analyze the hypocentral volume of the Krn Mt. earthquakes in Slovenia (Figure 6). Most recently, Croatian scientists use ambient microtremor recordings to constrain shallow soil structures and gain more insight into composition of the uppermost soil layers. The method used relies on a well known horizontal-to-vertical spectral ratio (HVSR) technique (Nakamura, 1989). Under certain assumptions, the observed HVSR amplitudes can be related to soil properties, most notably the thickness of sediments over the bedrock. If dense measurements are available, one can image the shallow structures, as has been done in the case of one neighbourhood in Zagreb (Figure 7). Dark shades in the profile shown in the bottom part of the figure correspond to high HVSR values. The lines are drawn to emphasize features, and have no direct geological interpretation, although clear systematic increase of the fundamental frequency with the thinning of the sedimentary cover close to B is evident. Such measurements will serve as the basis for future microzonation of Zagreb.

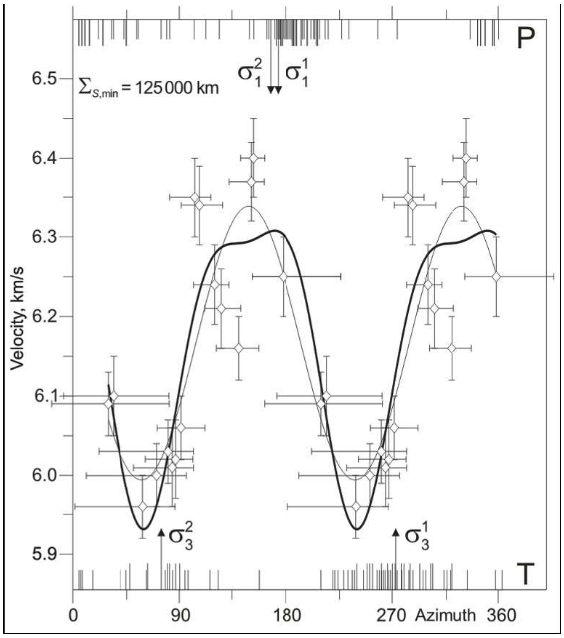

Figure 6. Observed (diamonds) P-velocity variation with azimuth in the hypocentral volume of Krn Mt. earthquakes of 1988. Thick and thin lines are fits to theoretical anisotropy model. The bars along the bottom and the top axes mark the orientation of T- and P-axes, respectively, obtained from fault-plane solutions of individual events from the Krn Mt. sequence. The large arrows are directions of the minimum (σ3) and maximum (σ1) principal stress in the focal region (after Herak at al., 2003).

3 Conclusions

The stage for rapid development of methods to solve inverse problems in seismology was set about the turn of the 19th into the 20th century. At that time the seismographs evolved to the stage which enabled recording earthquake ground motions with satisfactory faithfulness and timing accuracy. The world-wide and regional seismographic stations reached critical density and quality of maintenance, which guaranteed sufficient number of measurements to deal with ill-posed and overdetermined problems.

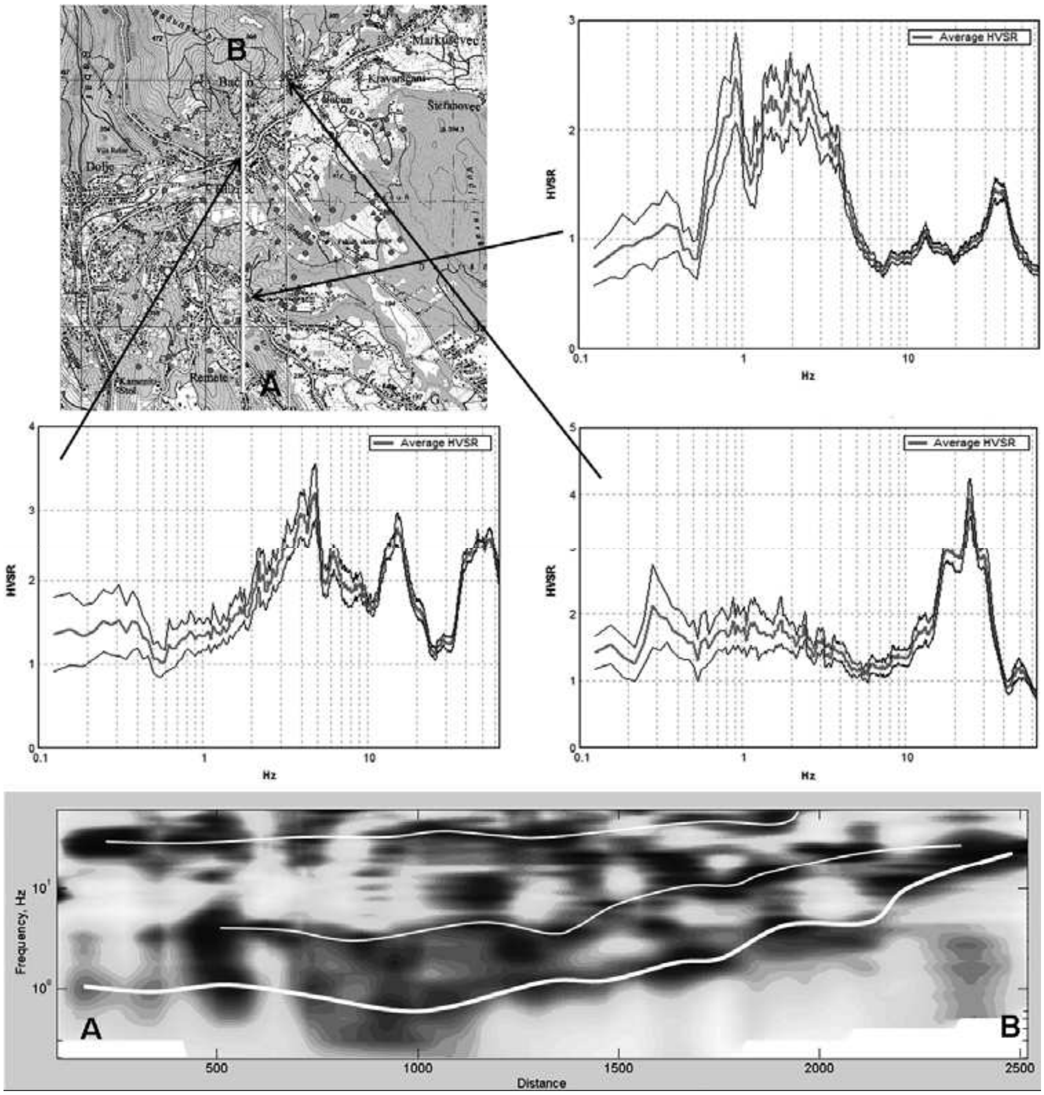

Figure 7. *Top left:* Map view of an area in Zagreb which was chosen as a test neighbourhood for the HVSR measurements. Black dots show the locations of measurement points. The foothills of the Medvednica Mt. are in the northern and north-western part. The white AB-line shows the location of the profile in the bottom. *Top right and middle:* Examples of the measured HVSR spectra (mean ± 1 standard deviation), showing how the dominant frequency shifts towards higher values as we move along the profile from A to B. *Bottom*: HVSR profile AB (see the map on the top). Only measurements within 500 m from the profile line are considered (after Herak, 2008).

In only a few following decades, the Earth revealed its well kept secrets, and we learned of its constitution with unprecedented detail. In 1906 R. D. Oldham noticed that longitudinal waves from large earthquakes recorded beyond the epicentral distance of 120° were substantially delayed, which he explained by the presence of the Earth's core with an approximate radius of 1600 km. This was the first major discovery regarding the composition of the Earth's interior using seismological data. It was followed by Mohorovičić's work (see above), and the discoveries of the core–mantle boundary by B. Gutenberg (1914) and of the inner core by I. Lehman (1936).

In subsequent years, as instrumentation developed and the computing power increased, we learned to use the same basic principles as the founding fathers of seismology did many years ago, to find where the oil and ore deposits lie, or to map lateral inhomogeneities deep below the surface. Seismic tomography and other seismic methods keep proving themselves as indispensable tools in exploring the interior of our planet.

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References

Agamennone G. (1906): *La Registrazione dei Teremoti*, Casa Editrice “L’Ellettricista”.

De la Haute-Feuille G. (1703): *Microscope micrometique ... avec un moyen de faire des Observation sur les Tremblement de Terre, et les pouvoir prèdire*, Paris.

Dewey J. and Byerly P. (1969): *The Early History of Seismometry (to 1900),* Bull. Seism. Soc. Am., 183-227.

Ewing J.A. (1883): *Earthquake measurement,* Memoires of the Science Dept., Univ of Tokyo, No. 9.

Ferrari G. (ed.) (1992): *Two Hundred Years of Seismic Instruments in Italy 1731-1940.* Storia Geofisica Ambiente, Bologna, pp 155.

Gutenberg B. (1914). *Über Erdbebenwellen*, VII.A Beobachtungen an Registerierungen von Fernbeben in Göttingen und Folgerungen über die Konstitution des Erdkörpers, Nachr. Ges. Wiss. Göttingen, Math. Phys. Kl., 1-52, 125-176.

Herak M. (1990): *Velocities of body waves in the Adriatic region.* Bolletino di Geofisica Teorica ed Applicata, XXXII, No. 125, 11-18.

Herak M., Živčić M. and Herak D. (2003): *Azimuthal anisotropy of the P-wave velocity in the hypocentral volume of the Krn Mt. (Slovenia) earthquake sequence*, Journal of Applied Geophysics, 54, 3-4, 257-264.

Herak M. (2008): *Recent applications of ambient vibration measurements in Croatia*, In: Increasing Seismic Safety by Combining Engineering Technologies and Seismological Data (J. Cassidy, M. Herak, M. Mucciarelli, Eds.), NATO Science Series, Springer, submitted.

Herak D. and Herak M. (1995): *Body-wave velocities in the circum-Adriatic region*, Tectonophysics, 241, 121-141.

Lehmann I. (1936). P', Bur. Ctr. Seism. Int. A 14, 3-31.

Lokmer I. and Herak M. (1999): Anisotropy of P-wave velocity in the upper crust of the central External Dinarides, Studia Geophysica et Geodaetica, 43, 345-356.

Mohorovičić A. (1910a): *Potres od 8. X 1909.*, Godišnje izvješće Zagrebačkog meteorološkog opservatorija za godinu 1909., 9/4,1-56. (in Croatian)

Mohorovičić A. (1910b): *Das Beben vom 8. X. 1909.*, Jahrbuch des meteorologischen Observatoriums in Zagreb (Agram) für das Jahr 1909., 9/4, 63 pp.

Mohorovičić A. (1910c): *Earthquake of 8 October 1909* (translation), Geofizika, 9, 1992, 3-55.

Mohorovičić A. (1913): *Razvoj sizmologije posljednih pedeset godina* (Development of seismology in the last fifty years), Annals of Yugoslav Academy of Science and Arts, 27, p.6. (in Croatian)

Mohorovičić A. (1924): *A critical review of the seismic instruments used today and of the organization of seismic service*, Bull. Seism. Soc. Am., 14, 38-59.

Nakamura Y. (1989): *A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface.* Quart. Rep. Railway Tech. Res. Inst., 30, 25-33.

Oldham R. D. (1906): *Constitution of the interior of the earth as revealed by earthquakes*, Quart. J. Geol. Soc. 62, 456-475.

Perry J. and Ayrton W. E. (1879): *On a neglected principle that may be employed in earthquake measurements*, Phil. Mag. ser. 5, Vol. 8, 30-50.