The First Very Broadband Mediterranean Network: 30 Yr of Data and Seismological Research

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Abstract

Starting in 1988, with the installation of the first broadband (BB) instrument in Italy, the Mediterranean Very Broadband Seismographic Network (MedNet) program established a backbone network of BB stations of the highest quality in the Mediterranean Sea countries. The Mediterranean region is characterized by relevant and frequent seismicity related to its complex tectonics, due to the convergence of two major plates, Africa and Eurasia, and the involvement of other minor plates, as the Adriatic plate. Therefore, the MedNet project became a scientific research infrastructure of excellence, able to fill the gap of regional coverage when the availability of seismic BB instruments was still scarce. The main characteristics of the MedNet network are the highest quality of the seismographic instrumentation at remote sites and very low level of anthropogenic noise with stable conditions of pressure and temperature. After 30 yr of recordings, the MedNet program has proven that the early adoption of very BB instruments in selected sites have been the best choice. A large number of studies benefited from MedNet data, as seismic source computation and Earth structure reconstruction, at local and global scale.

We present a concise overview of the contribution given by MedNet data in the last three decades to motivate and financially support the existence of this valuable infrastructure, and to further maintain this project.

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Supplemental Material

Introduction

The MedNet project started in 1987 with the financial support of the World Laboratory of Geneve (Plato-1 project; Boschi *et al.*, 1988, 1991). It was the early time of very broadband (VBB) seismometry with the ambitious purpose to collect with a single instrument, in a single record, a wide spectrum of seismic signals to fill the traditional gap between short-period (periods 1 s) and long-period seismology (periods 20 s). This was a great step forward in seismic data collection, where it was common to have different instruments recording narrow ranges of signal frequencies. The need of VBB seismometers came from the scientific community interested in global seismology studies, because these instruments are able to resolve the lowest frequencies of Earth's tides and free oscillations that are primarily used in understanding the deep interior of the Earth. The important advantage, in comparison to broadband (BB) seismometers, is their ability to record frequencies around and below 0.001 Hz (period 1000 s). As Wielandt and Steim (1986) stated, "The most obvious argument in favor of such VBB system is that it does not a priori determine the seismological research".

In the early 1980s, the production of the new high-performance Streckeisen STS-1 instrument (360 s–10 Hz, 144 dB dynamic range) pushed the research toward global seismology studies. At the same time, Quanterra started to commercialize the first digitizers at 24 bit digitizers, the Quantagrator. The new instruments were employed in the development of the first VBB networks, such as Incorporated Research Institutions for Seismology (IRIS), U.S. Geological Survey (USGS) Global Seismographic Network (GSN; U.S.A., worldwide network, Lay *et al.*, 2002, and references therein; see Data and Resources), GEOSCOPE (France, worldwide network, Roult *et al.*, 2010; see Data and Resources), POSEIDON (Japan, Eastern Pacific network, Ohtake and Ishikawa, 1995), YELLOWKNIFE Array (now part of the Canadian National Seismograph Network,

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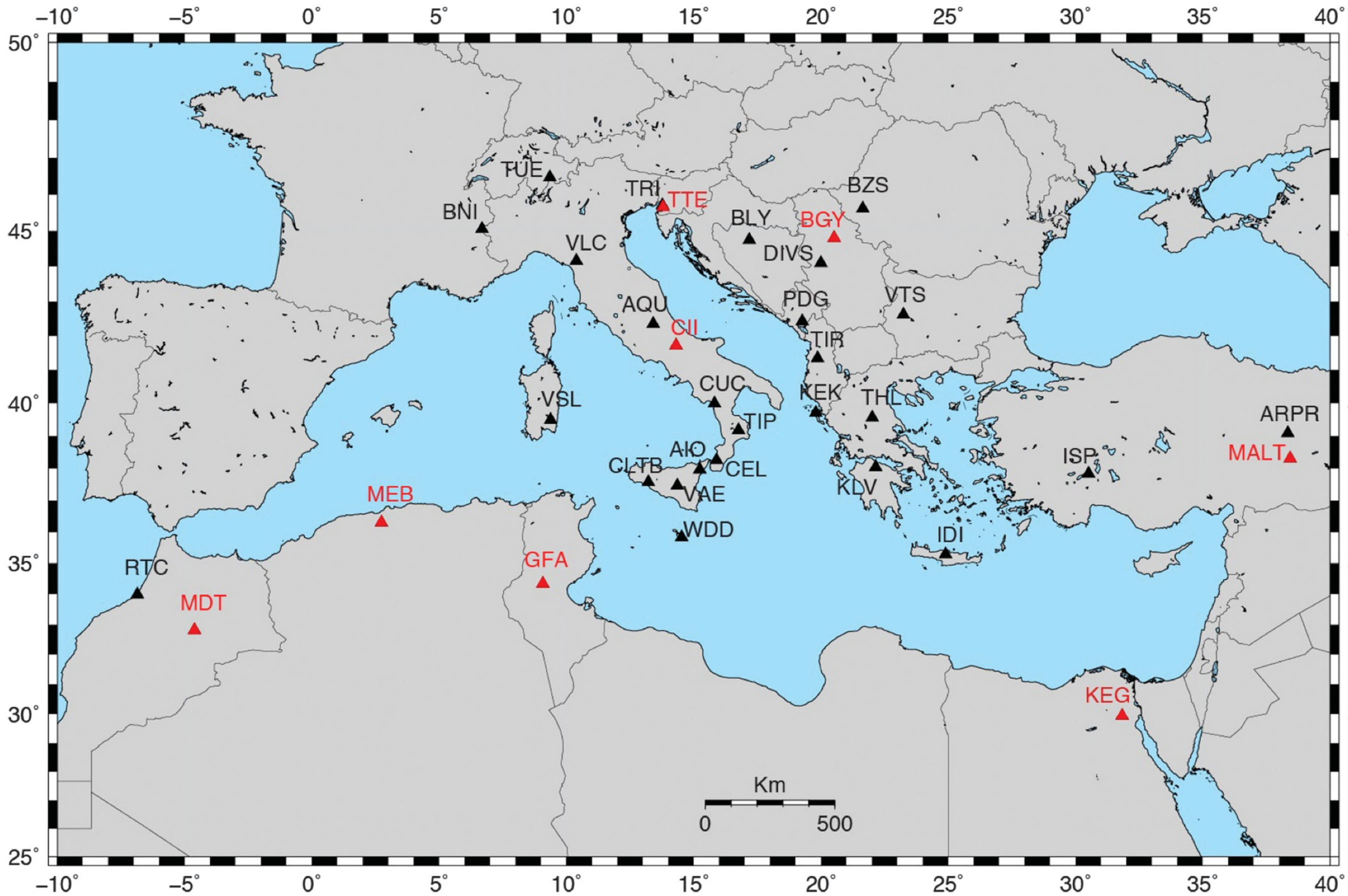


Figure 1. Map of the Mediterranean Very Broadband Seismographic Network (MedNet) updated on 28 February 2019 (see Data and Resources); closed stations are shown in red.

see Data and Resources), or GRN (Germany, see Data and Resources).

In Italy, MedNet started in 1988 with the first station AQU located in L'Aquila (Fig. 1), followed by BNI (Bardonecchia, Western Alps) and VSL (Villasalto, Sardinia). After a short test time, the program expanded to other regions around the Mediterranean Sea (Table 1 and Fig. 1). From 1989 to 1992, seven stations were permanently installed: four of them were located in northern Africa, namely in Tunisia, Algeria, Egypt, and Morocco (Giardini *et al.*, 1992). Meantime, attempts to install instruments in Pakistan and Iraq were also considered, but unsuitable to be host seismic stations, due to the complexity of the local conditions. 30 yr after the first installation, the MedNet (MN) network managed a total of 35 stations, and at the moment of writing, 26 stations are fully operating (European Integrated Data Archive, see Data and Resources).

Simultaneously with the VBB stations spreading in the Mediterranean region, MN program started a data center where data recorded on magnetic tapes were collected, processed, archived into SEED volumes, and sent to IRIS (Aster *et al.*, 2005; see Data and Resources) for data distribution. The data processing and archival was time consuming and data became available only several months after the recording time. At the end of the 1990s, after the occurrence of the 1997 Colfiorito sequence (later described in the Contributions to Seismic Source Studies section), MN dataset became promptly available so that the worldwide scientific community greatly benefited from quasi-real-time accessibility of this high-quality data (see MedNet bibliography in the supplemental material to this article).

The Mediterranean, one of the most populated regions of the Earth, is a geodynamically active region hit by strong earthquakes and one of the most populated regions of the Earth. With this regard, the scientific goal of the MedNet program was to collect high-quality seismic data to study, for the first time, the deep and shallow structure beneath the entire basin with high resolution.

Global digital seismic networks (i.e., GSN, GEOSCOPE), since the mid-1970s, provided a large amount of seismic data allowing a global geographical coverage, especially important for teleseismic studies. In addition, a better knowledge of seismic sources for moderate magnitude events is fundamental to understand the earthquake mechanism and to improve the earthquake hazard assessment in the seismically active Mediterranean region. At the same time, the deployment of VBB networks worldwide provided waveforms with an

TABLE 1
Mediterranean Very Broadband Seismographic Network Stations

Station Name	Site Name	Starting Time	Closing Time	Latitude (°)	Longitude (°)	Elevation (m)
AIO	Antillo, Italy	2000/01/01	2012/05/30	37.97	15.23	751
AQU	L'Aquila, Italy	1988/08/01	—	42.35	13.40	710
ARPR	Arapgir, Turkey	2014/01/23	—	39.09	38.34	1537
BGY	Beograd, Serbia	1991/03/26	2001/12/31	44.80	20.52	250
BLY	Banja Luka, Bosnia and Herzegovina	2009/05/21	—	44.75	17.18	256
BNI	Bardonecchia, Italy	1988/04/30	—	45.05	6.68	1395
BZS	Buzias, Romania	2005/11/23	—	45.62	21.64	260
CEL	Celeste, Italy	2003/10/29	—	38.26	15.89	702
CII	Carovilli, Italy	1994/10/19	2006/06/23	41.72	14.30	910
CLTB	Caltabellotta, Italy	2000/09/07	—	37.58	13.22	949
CUC	Castrocucco, Italy	2003/07/16	—	39.99	15.81	637
DIVS	Divcibare, Serbia	2005/07/14	—	44.10	19.99	1000
DPC	Dobruska/Polom, Czech Republic	1993/01/01	—	50.35	16.32	748
GFA	Gafsa, Tunisia	1989/06/10	1999/12/31	34.34	9.07	250
IDI	Anogia, Greece	1994/10/02	—	35.29	24.89	750
ISP	Isparta, Turkey	1996/10/24	—	37.84	30.51	1100
KEG	Kottamya, Egypt	1990/12/03	1999/12/31	29.93	31.83	460
KEK	Kerkira, Greece	2000/03/02	—	39.71	19.80	227
KLV	Kalavryta Achaia, Greece	2014/01/23	—	38.04	22.15	758
MALT	Malatya, Turkey	2000/05/26	2011/12/31	38.31	38.43	1120
MDT	Midelt, Morocco	1989/11/15	1999/12/31	32.82	−4.61	1200
MEB	Medea, Algeria	1992/05/20	1994/08/31	36.30	2.73	500
PDG	Podgorica, Montenegro	2008/07/18	—	42.43	19.26	40
RTC	Rabat, Morocco	2002/07/22	—	33.99	−6.86	50
THL	Klokotos Thessalia, Greece	2006/11/28	—	39.56	22.01	86
TIP	Timpagrande, Italy	2003/09/10	—	39.18	16.76	789
TIR	Tirana, Albania	1994/07/13	—	41.35	19.86	247
TRI	Trieste, Italy	1996/05/15	—	45.71	13.76	161
TTE	Trieste, Italy	1991/01/22	1995/04/06	45.66	13.79	92
TUE	Stuetta, Italy	2001/11/14	—	46.47	9.35	1924
VAE	Valguarnera, Italy	2000/01/01	—	37.47	14.35	735
VLC	Villacollemandina, Italy	2001/01/01	—	44.16	10.39	555
VSL	Villasalto, Italy	1989/07/19	—	39.50	9.38	370
VTS	Vitosha, Bulgary	1996/05/10	—	42.62	23.23	1490
WDD	Wied Dalam, Malta	1995/07/06	—	35.84	14.52	44

excellent signal-to-noise ratio in the intermediate- to low-frequency band to be used in the seismic moment tensor inversion for regional events with magnitude down to 5.0. This was particularly important in the Mediterranean region where moderate earthquakes may be catastrophic (Di Luccio *et al.*, 2005; Pino and Di Luccio, 2009).

Here we show how MN data in 30 yr of data acquisition and archival has been used in pioneering seismological studies, from seismic source to Earth structure, as tomography, receiver functions (RFs), and so on. We also give a summary of the present state of the MN network, and we suggest some research that can be done in the future using data recorded by this VBB network in the Mediterranean region. Although the following short description of research and techniques is not exhaustive, it shows the importance of maintaining and supporting the MN network, in light of the number of papers that researchers have done and can still do using VBB waveforms.

History and Technological Advances Within Mednet

The MN network presently comprises 26 stations (Table 1 and Fig. 1) equipped with 18 Streckeisen STS2/120 s and six STS1/VBB. The Streckeisen STS2 exhibits a flat velocity response between 0.00833 and 30/50 Hz, while the Streckeisen STS1 covers the range between 0.00278 and 10 Hz (Wielandt and Streckeisen, 1982; Wielandt and Steim, 1986). The high resolution in this wide-frequency band makes the MN network so peculiar. In particular, the six STS1 sensors still operational (Fig. 1) were installed during the early phases of the program, following innovative and strict installation rules. As foreseen by the producer, these sensors were installed using the provided shielding and operated inside glass bells under a moderate vacuum, which ensures protection from environmental conditions and is thermally isolated. Additional insulating boxes are added around these glass bells. When the STS1 sensors were discontinued, MN moved toward Streckeisen STS2 that were initially installed with usual and relatively simple thermal insulation, which however resulted in relatively high nonseismic noise at the long period. Successively, STS2 instruments were reinstalled according to Wielandt's recipe (Wielandt, 2002), on a marble base inside and a hermetically sealed container composed of a combination of copper, aluminum, and steel shields filled with glass fiber and foam. Additional improvements included the use of an electric shielding to the base or a mu-metal shielding to further reduce noise from magnetic perturbations at some stations.

When MN program started, particular attention was given to the selection of sites (Mazza *et al.*, 2008). Remote underground sites such as abandoned mines, old tunnels, or ancient water cisterns were preferred locations as AQU (L'Aquila, central Italy), BNI (Bardonecchia, western Alps), VSL (Villasalto, Sardinia), MDT (Midelt, Morocco), and GFA (Gafsa, Tunisia; see Fig. 1 for geographical locations). On one side, thermal stability and a low level of anthropogenic noise made their locations particularly attractive. On the other side, remoteness and lack of infrastructure of these sites required very complex installations and maintenance become a difficult task, both for MN staff and for local partners. Thus, in the following years, extreme site locations have been abandoned, but a meticulous inspection is still adopted in the station installation and operation to ensure the best quality of the data.

In the late 1980s, the only 24-bit digitizer available, the Quanterra, was installed at the MN sites. At present, many 24-bit digitizers are available, and the choice depends on the technical specifications as well as on their costs.

Network Performance

In the 30 yr of operation, the MN network managed a total of 35 stations, although at present they are 26. To show the overall station quality during the running period of each MN station, we computed the distribution of seismic power spectral density (PSD) in the direct Fourier method (Cooley and Tukey, 1965) based on the routine used by and implemented in the ObsPy (McNamara and Buland, 2004; Krischer *et al.*, 2015) software. The PSD allows us to identify the ambient noise conditions as high-probability occurrences, and it is a standard tool to examine site artifacts related to station operation and the Earth noise level at each site.

In Figure 2, we show the median of the PSD for the vertical and east components of the 35 MN stations, calculated for the entire running period. As expected, the ambient noise at all sites and components is below the new high-noise model (NHNM) level for the whole frequency range. In particular, focusing at long periods (>20 s), the noise level is 40–50 dB below the NHNM for the vertical components and ~25 dB for the horizontal ones. Some stations show a higher long-period noise (KEK, AIO, CLTB, MALT, and CII), mainly due to sensor changes and problems with the shielding and vacuum systems not always promptly solved. However, most of the stations had stable instrumentation history (no major issues) documented by a low long-period noise level, especially on the vertical components. The horizontal components show a higher noise level mainly influenced by the sensor-to-ground coupling, atmospheric pressure changes, and wind (e.g., Webb, 2002). High-noise levels at short periods are mainly found at those stations installed nearby city centers.

Overall, the noise performance confirms the high value of the MN data, suitable for long-period seismological studies. It is worth to remember that noise level has changed over time during the long running period of the network, and our analysis here has the only goal to show the overall station performance. A more detailed report on the network performance will be the subject of a future study.

Seismological Studies

In the following paragraphs, we summarize the results of the most representative seismological studies based on or including MN data, although an extended but not exhaustive list is reported in the supplemental material.

In the last 20 yr, the availability of waveforms from MN BB stations has been fundamental to retrieve the characteristics of the source of significant Italian earthquakes. MN data also

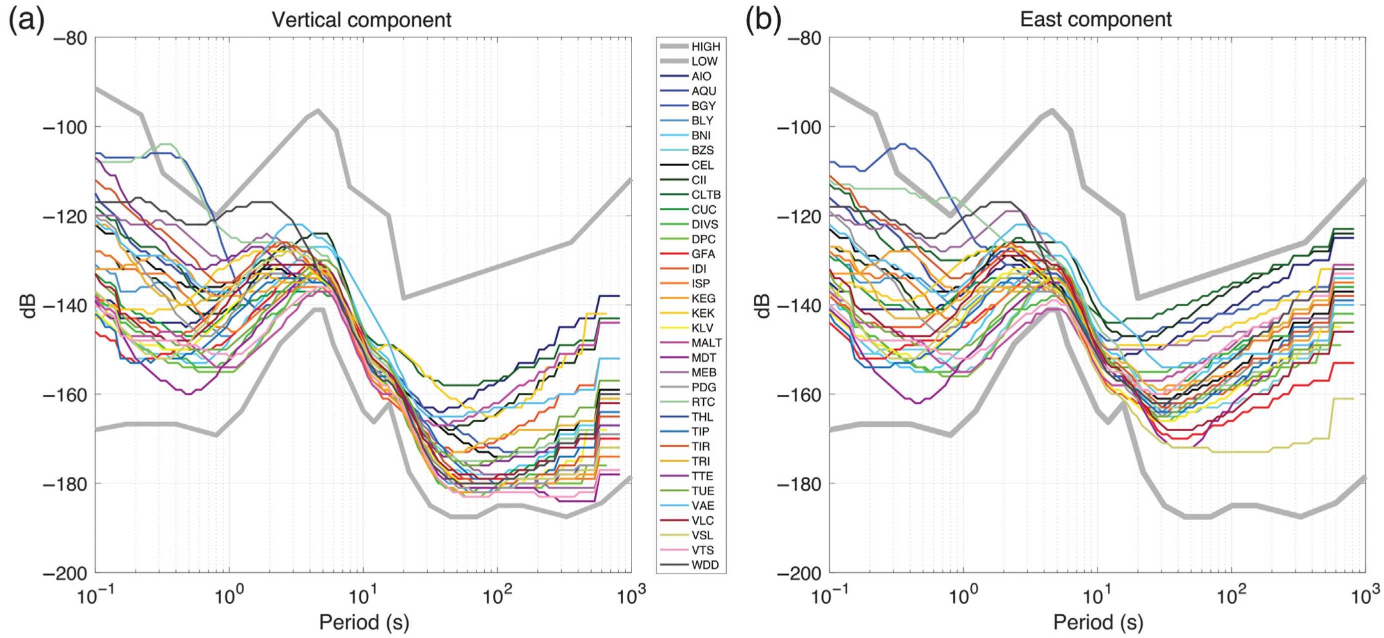


Figure 2. Median curves of the power spectral densities of the (a) vertical and (b) east component for the stations listed in Table 1 from the installation date to 2018. Each line represents a single station. Thick gray lines correspond to the new high-noise model and new low-noise model.

contributed to the reconstruction of shallow, intermediate, and deep structure of the Mediterranean basin, using a large number of techniques.

Contributions to Seismic Source Studies

At the end of the 1980s, worldwide seismicity was nearly routinely analyzed using global data, and moment tensor catalogs, for example, in the National Earthquake Information Center (NEIC) Bulletin, the Global Centroid Moment Tensor (CMT) catalog (Dziewonski *et al.*, 1981), and the USGS dataset (Sipkin, 1986), were available including events occurred since 1977.

The deployment of MN regional network allowed to increase the data availability in the Mediterranean region and to study the seismic source of regional and teleseismic earthquakes. The earlier studies used the MN waveforms to compute moment tensor solutions for global largest earthquakes (Giardini, 1992; Giardini and Beranzoli, 1992; Beranzoli *et al.*, 1993; Giardini *et al.*, 1993, 1994). Their results have been compared to the available moment tensors of the NEIC Bulletin, of the Global CMT catalog and of the USGS dataset, and the agreement was very good, demonstrating the high quality of the regional waveforms recorded at the MN stations.

In the 1990s, seismic source studies using MN data demonstrated that data from regional networks fill the coverage gap of global networks and greatly contribute to source parameter determination, in terms of seismic moment tensor and source time functions. A significant contribution came from the 1997 Colfiorito seismic sequence that started with the 26 September 1997 M 6 earthquake. In nearly a month, six events with a magnitude M_w between 5 and 6 struck the Umbria–Marche region (central Italy), causing 11 deaths and damaging historical buildings. This sequence gave the opportunity to modify the original Global CMT algorithm to allow moment tensor inversion of long-period waveforms for moderate earthquakes, M_w 5.5, at local and regional distances (less than 15°, Arvidsson and Ekström, 1998). The Regional CMT (RCMT) project completely based on MN data began. For the strongest earthquakes of the sequence, RCMTs were computed rapidly because MN stations (AQU, CII, BNI, TRI, and VSL) could be readily downloaded in real time by a modem connection and directly used in the source parameters inversion. The obtained Quick RCMT solutions (QRCMT) were published on a dedicated MN webpage (see Data and Resources). In the paper by Ekström *et al.* (1998), the procedure, applied to $M > 4.7$ events of the 1997 seismic sequence, is described. Since then, the QRCMT procedure is automatically applied to every $M > 4.5$ earthquake occurring in the Mediterranean region (Morelli *et al.*, 2000; Pondrelli *et al.*, 2002). This procedure led to the construction of the European–Mediterranean RCMT catalog, which is regularly updated and available online (Fig. 3; see Data and Resources, Pondrelli *et al.*, 2002, 2004, 2006, 2007, 2011; Pondrelli and Salimbeni, 2015).

Later, when the 2002 Molise (southern Italy) earthquake occurred, the moment tensor computation technique time-domain moment tensor (TDMT, Fukuyama and Dreger, 2000) was applied for the first time to the whole sequence recorded at the MN stations (Di Luccio *et al.*, 2005). The BB waveforms were automatically gathered via internet or dial-up connection for the earthquakes larger than 3.5 and inverted to retrieve the best focal mechanism solution. The difference between the TDMT and the RCMT techniques is that the latter is based

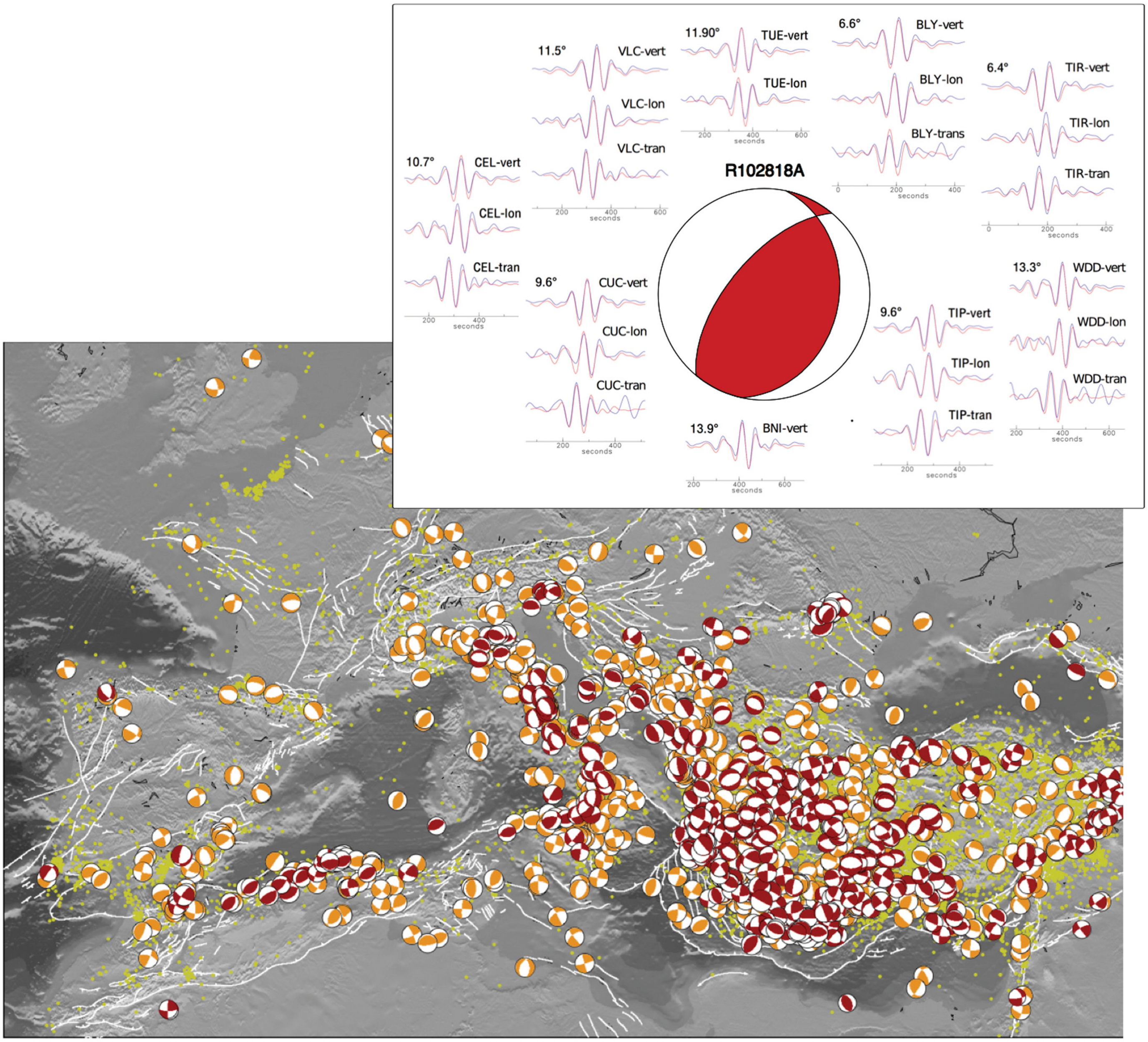


Figure 3. Map of the centroid moment tensor (CMT, red) and Regional CMT (RCMT, orange) solutions available for earthquakes occurred between 1977 and 2018, showing the improvement given to seismic sources catalogs by very broadband regional networks as MedNet. (Inset) Example of real (blue) and synthetics (red) waveforms from MedNet station, used to compute the RCMT of an M_w 5.6 earthquake occurred in Romania on 10 October 2018. For each set of waveforms is reported the station name and components (top right) and angular distance between hypocentral location and the station (top left).

on long-period waveform inversion ($T > 35$ s) and allows to estimate seismic source parameters for events as small as 4.5 magnitude, rarely down to 4.0, whereas the first one allows to compute source parameters for smaller magnitudes, using waveforms band-passed according to the earthquake size and the epicentral distances.

Currently, the TDMT solutions are automatically computed for the Italian earthquakes with $M_L \geq 3.5$, and MN data contribute along with stations of the Italian Seismic National Network (see Data and Resources). The algorithm inverts local to regional three-component BB velocity waveforms starting from a preliminary hypocentral location, to compute the seismic moment tensor in a point-source approximation (for further details, see Scognamiglio *et al.*, 2009). The automatic solutions with high-quality values and all the manually revised solutions are published on a dedicated website (see Data and Resources). At present, the TDMT catalog contains more than 900 moment tensor solutions. The real-time availability of MN data also allowed TDMT detailed studies on the main Italian

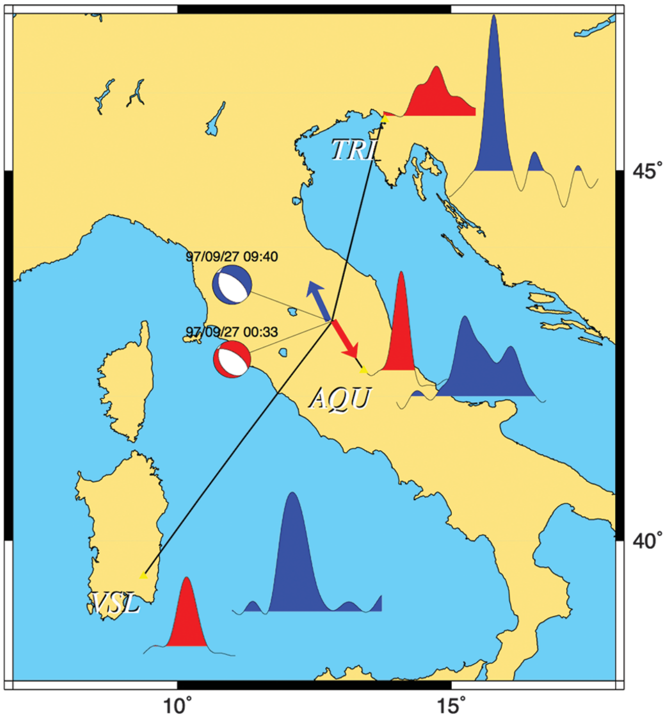


Figure 4. Directivity evaluated comparing the relative moment rates for the two major shocks of the Umbria–Marche 1997 seismic sequence (S. Mazza, personal comm., 2019).

seismic sequences of the last 10 yr (Scognamiglio *et al.*, 2010, 2012, 2016; Chiaraluce *et al.*, 2017).

The existence of MN high-quality stations and the prompt availability of waveforms were also crucial for the quasi-real-time study of the complex source characteristics of the 1997 Umbria–Marche mainshocks (M_w 5.7, 6.0, and 5.6). The empirical Green's function technique applied to the recordings obtained from AQU, TRI, and VSL has shown directivity effects for all of the three earthquakes. The two southernmost events had a rupture propagation toward southeast, whereas the other (and largest) one broke up in the opposite direction (Pino *et al.*, 1999; Fig. 4). This study pioneered in real-time seismology, and it was hereafter applied during the following significant seismic sequences in Italy. Lateral directivity effects of the mainshock of the 2002 Molise seismic sequence have been revealed studying surface waveforms of CII, along with teleseismic and regional data (Vallée and Di Luccio, 2005). Later, real-time availability of MN data allowed to improve the understanding of the source of the 6 April 2009 M_w 6.1 L'Aquila earthquake. A few hours after the mainshock, Pino and Di Luccio (2009) computed the relative source time functions at VLC, VSL, and CUC stations and were able to reveal that the earthquake occurred in two distinct subevents: a first one with fracture propagating northeastward from the hypocenter, followed by a second rupture patch located southeast of the previous one (Fig. 5).

Similarly, by carefully analyzing the waveforms of AQU and other six near-fault stations, Tinti *et al.* (2014) demonstrated that the first 3 s of up-dip rupture during the L'Aquila mainshock released only ~25% of total seismic moment, but strongly controlled the observed ground motion in the near source and explained the observed short duration of ground shaking in the L'Aquila town and surrounding areas.

In a more general view, MN data have been used in several studies to recover seismic source parameters in the Mediterranean. For instance, Melis and Konstantinou (2006) used BB records at KEK and IDI stations, in the eastern Mediterranean, for the real-time seismic monitoring of the Greek region; Roumelioti *et al.* (2009) used BB regional records from four MN stations (CEL, TIP, KEK, and WDD) to compute the slip distribution of the 2008 M 6.7 southern Peloponnese earthquake; Örgülü (2011) used records at ISP for source studies of small earthquakes in the North Anatolian fault.

Although a detailed list of articles about seismic source studies using MN data is beyond the scope of this article, it is important to mention those in which these data have contributed to improve the quality of the research and the scientific knowledge. This is the case for the Italian magnitude catalog computation. Since 1996, MN data greatly contribute to the characterization of source parameters of Italian earthquakes, in particular to the automatic computation of local magnitude M_L. The long-term availability of the earthquake-location catalog for magnitudes ranging from 0.8 to 5.6 allowed the calibration of the duration magnitude M_d with the M_L. The M_L was computed for each M_d in the catalog, going backward in time enough to recalibrate the whole instrumental Italian catalog, to have a consistent estimation of different magnitudes (Castello *et al.*, 2007). In addition, it is worth to note that the occurrence of the 1997 Umbria–Marche and the 2002 Molise sequences led to the above-described procedures to compute the RCMT and the TDMT, respectively, included also the estimation of the moment magnitude M_w, previously absent in the Italian seismicity catalog.

Contributions to earth structure

Since the early 1990s, data completeness and the increase in the number of European BB stations, together with the increase of the computational power, greatly contributed in improving the imaging of the European and Mediterranean deep structure. In particular, the deployment of MN stations in North Africa, Turkey, and the Balkan region allowed the unprecedented ray-path sampling in the Mediterranean basin. Data collected at the BB stations in the Mediterranean area were used in tens of body- and surface-wave (earthquake and ambient noise data) studies as well as full-waveform tomography, RF, and anisotropy studies. The overall target was the description of the 3D isotropic and anisotropic lithospheric and deep mantle structure of the region, in particular, the knowledge of the geometry of the main Mediterranean slabs and the anisotropy

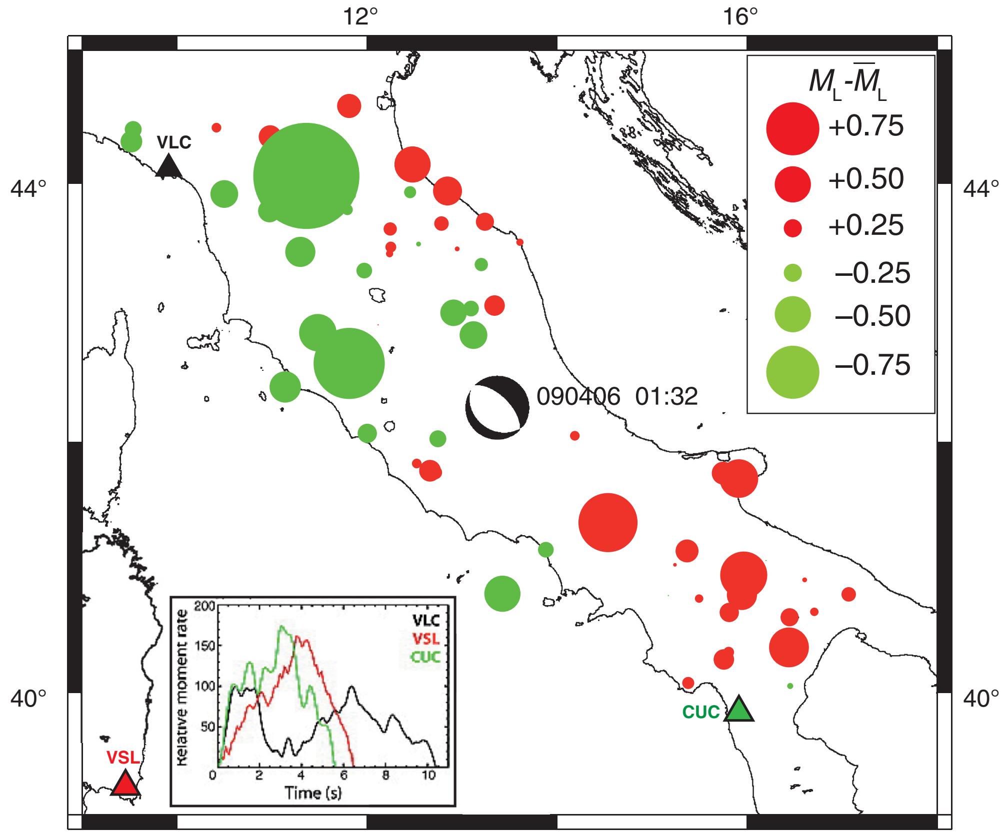


Figure 5. M_L of the mainshock as computed at the available stations of Italian Seismic National Network. Red (green) circles indicate station with M_L higher (lower) than the assigned M_L 5.8. The circle size is proportional to the magnitude difference (modified after Pino and Di Luccio, 2009). The Quick RCMT (see Data and Resources) along with the MN stations location are shown. (Inset) The unfiltered relative source time functions resulting at MN stations VLC, CUC, and VSL are displayed.

patterns. The 3D structure of the lithosphere and asthenosphere had (and still have) a central role in understanding the complex geodynamic evolution of the entire region. With this regard, Di Luccio *et al.* (2016) have shown that the high quality of MN waveforms along with ocean-bottom seismometer's data can be used to investigate the deep structure of the Tyrrhenian slab. The analysis of *P*-wave complexity and 3D modeling of the slab allow to study the structure beneath southern Italy using VBB waveforms from local deep earthquakes (Fig. 6).

Out of the Mediterranean area, MN data were used in many global studies of the Earth structure thanks to the data sharing policy that led it to be part of the IRIS community.

Tomography

MN data have been included in a long list of tomography studies, from global to local scale. We briefly refer here to some representative papers for which MN data have been crucial. We refer to the supplemental material for a more comprehensive bibliographic collection.

Starting from the global scale, Ekström *et al.* (1997) and later Boschi and Ekström (2002) included MN data in a global dataset of surface-wave dispersion measurements used to image the 3D seismic-velocity structure of the entire globe with a resolution of 2 × 2 degrees.

Thio *et al.* (1999) used data recorded at the westernmost MN stations to calibrate the seismic structure in the western Mediterranean region. They concluded that with an appropriated calibration of the seismic structure together with high-quality BB data, it was possible to characterize and study events, in terms of source mechanism and depth, even with a limited azimuthal distribution of regional BB stations.

Piromallo and Morelli (2003), as a reference study of regional 3D body-wave tomography, allowed to reconstruct the last 100 My evolution of multiple slabs that characterize the Mediterranean region. With the selection of *P*-wave phases from the International Seismological Centre catalog collected from 1964 to 1995 including MN data, the authors were able to image with great detail the 3D seismic structure of the Mediterranean mantle from 50 to 600 km depth. In Piromallo and Morelli's study, the location of MN stations, in particular those in northern Africa, as MDT, GFA, and KEG (Fig. 1 and Table 1), was certainly crucial.

Li *et al.* (2010) presented a surface-wave dispersion study applying the ambient noise method to BB data recorded at most of the seismic Italian network, including MN stations. About 2 yr data of vertical-component ambient noise were cross-correlated for station pairs to estimate fundamental-mode Rayleigh-wave Green's functions in the Italian peninsula. Their results clearly showed that the Tyrrhenian Sea is characterized by higher velocities below 8 km than the peninsula and the Adriatic Sea.

Zaccarelli *et al.* (2011) retrieved changes in crustal seismic velocity in the L'Aquila region (central Italy) by analyzing more than 2 yr of data of cross correlations of ambient seismic noise. They observed a decrease of seismic velocities in the crust as a consequence of 2009 L'Aquila mainshock.

Zhu *et al.* (2012) created a tomographic model of the European upper mantle performing a full-waveform inversion

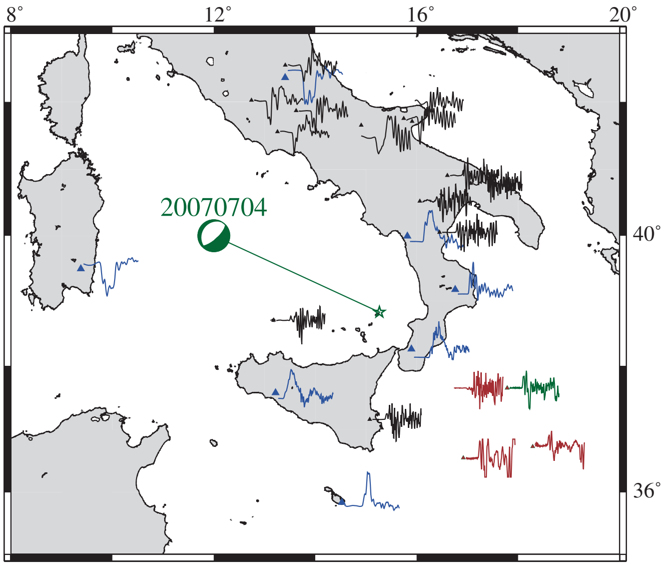


Figure 6. Waveforms of the 4 July 2007 *M* 5.2 event (green star) occurred at 279 km depth in the Tyrrhenian Sea. In map-view, we report the vertical component of the seismograms recorded at MN stations (blue), and at ocean-bottom hydrophones and ocean-bottom seismometers (brown and green, respectively) in the Ionian sea. Waveforms are windowed 5 s before and 15 s after the *P* onset. The source-to-receiver ray paths reveal significant differences at receivers, which are perpendicular to the trench with respect to other stations. Stations along the Calabrian arc show high frequency in the *P* train compared to the other stations. Slab geometry as well as deep structure can be successfully investigated by modeling the *P* wave at different stations (Li *et al.*, 2014).

of three-component seismograms with an iterative inversion strategy involving adjoint methods. They found fast seismic-wave velocities beneath Scandinavia and Alps to Dinarides belts, and slow velocities beneath the northern Rhine graben (central Europe).

Among others, Greve *et al.* (2014) in their regional study were able to interpret the *S*-wave velocity upper-mantle structure of the Mediterranean in terms of (de)hydration mechanism acting in the asthenosphere. The resolution of the images, especially in the south, strongly depends on the MN stations in North Africa.

RFs

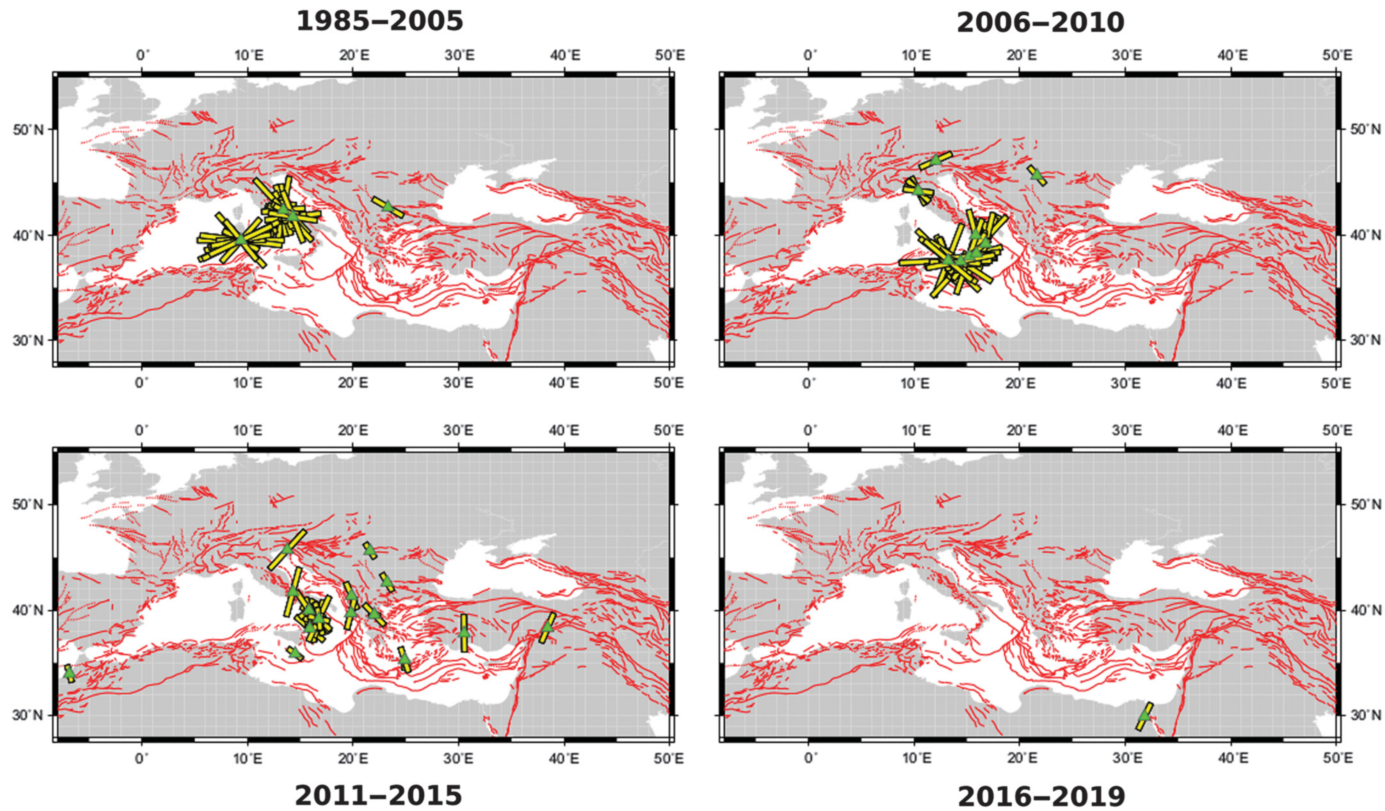
The paper by Megna and Morelli (1994) was the first pioneering study on RFs analysis based on teleseismic waveforms, recorded by an MN station, AQU. They found that the structure beneath AQU is characterized by an almost 33-kilometer-thick homogeneous crust with the Moho north-northwest dipping. Later, Megna *et al.* (1995) applied the same technique to also study the crustal structure under the MN station VSL, in Sardinia (Fig. 1 for location). Their study carried out some interesting conclusions as the small amplitude of *P*-to-*S* phase, generated at the Moho discontinuity, related to a small velocity gradient and the small back-azimuthal variations of the same phase consistent with a velocity model in which the Moho is horizontal.

van der Meijde *et al.* (2003) used data recorded at three MN stations relatively apart as VSL, MDT, and KEG, to derive the crustal structure in the Mediterranean region using RFs. They found a Moho depth at 29 km beneath VSL, in good agreement with Megna *et al.* (1995). Although studies by Megna and Morelli (1994), Megna *et al.* (1995), and van der Meijde *et al.* (2003) used the same upper-mantle velocity ($V_P = 7.9$ km/s) in determining the Moho depth underneath VSL, in the latter study a 1–2-kilometer-thick sedimentary layer was found, whereas in the first two studies a mid-crustal discontinuity was mapped at 21–25 km depth. The Moho beneath KEG (Egypt) was found at 32 km deep, whereas at MDT at 39 km, in agreement with the expected thick crust beneath the Atlas Mountains.

The RFs approach with teleseismic data was also used by Mele *et al.* (2006) to investigate the crustal thickening beneath the central Apennines (Italy). They selected all the earthquakes located at epicentral distances within 35°–90° recorded at the GeoModAp project array (Amato *et al.*, 1998) and at AQU. This analysis highlighted that in central Italy the crust–mantle discontinuity varies from a minimum of 22 km beneath the Tyrrhenian side to a maximum of 47 km beneath the Apennines. In the Adriatic Sea side, the Moho is located at 33 km of depth. This trend, consistent with the results obtained in the northern Apennines, is in contrast with previously inferred values (Marone *et al.*, 2003), that identified the maximum crustal thickness of 30–35 km along the chain. Another MN station, VLC, was used to investigate the deep crustal structure of the Apennine orogen. VLC station was part of the Retreating-Trench, Extension, and Accretion Tectonics (RETREAT) project (Levin, 2003), a temporary network consisting of 50 BB seismic stations deployed across the northern Apennines from 2003 to 2006. Exploiting the RFs technique on the dataset collected at the RETREAT temporary network, Margheriti *et al.* (2006) identified the Moho geometry and also the possible top of the Adria descending slab at a depth of 80–90 km beneath VLC, giving a reasonable solution to discrepancies between previous RFs studies.

Bianchi *et al.* (2010) applied the RFs harmonic decomposition to retrieve the isotropic structure under the seismic stations and also to identify the presence of anisotropic bodies to the teleseismic dataset recorded by the RETREAT project network (including VLC). A trench-normal-oriented anisotropic body was found trapped between the Adriatic and Tyrrhenian Moho discontinuities. It could not be interpreted as subducted crust due to the depth extent of its apparent anisotropy, and Bianchi *et al.* (2010) supposed that it was the remnant of the delamination of the Adriatic microplate continental lower crust.

Herrmann *et al.* (2011) simultaneously inverted the *P*-wave RFs obtained for the MN station AQU together with the dispersion data to obtain the velocity model of the central



Apennines. This velocity model is at present the one routinely used for the Green's function computation in the TDMT procedure (Scognamiglio *et al.*, 2010).

In many continental regions, *S*-to-*P*-converted waves from interfaces below the Moho have been associated with the lithosphere–asthenosphere boundary (Ford *et al.*, 2010). Investigating these phases at stations of the Italian Seismic National Network and MN network, Miller and Agostinetti (2012) attributed thicknesses between 60 and 170 km (with an average of ~90 km) to the Italian continental lithosphere. Their conclusion evidenced that active subducting lithosphere exists beneath the northern Apennines and Calabrian arc, whereas it is absent elsewhere.

Seismic attenuation

The MN stations contributed also to study the regional body-wave attenuation characteristics (apparent Q) along selected Italian and Mediterranean source to receiver paths. The high quality of the recordings, due to the quality of instruments and deployments, has allowed seismologists to estimate stable source spectra and to apply a coda source normalization method to determine apparent attenuation for the regional seismic phases *Pn*, *Pg*, *Sn*, and *Lg* traveling from central Apennines to six of the MN stations (Walter *et al.*, 2007). Seismic stations in central Apennines showed very strong attenuation compared to those in the eastern and western Alps, where the relative Q-values were much larger.

Later, Pasyanos *et al.* (2009) presented a BB tomographic model of *Lg* attenuation in the Middle East derived from source-

Figure 7. Shear-wave splitting measurements at the MedNet stations (green triangles) in the western and central Mediterranean region as taken from splitting databases (Wüstefeld *et al.*, 2008; Barruol *et al.*, 2009) for four time windows. Each single line in yellow corresponds to a single measurement, oriented with the fast axis direction and scaled with the delay time value.

and site-corrected amplitudes of crustal earthquakes, recorded at more than 50 BB seismic stations, including the MN station KEG. In the study region, they found strong correlations of the attenuation with both topography and tectonics.

Piccinini *et al.* (2010) analyzed *P*- and *S*-wave spectra from moderate to deep focus teleseismic events to investigate the variations of the Earth mantle attenuation in northern Italy. They included waveforms recorded at the BB seismic station VLC along with data from the RETREAT project (Levin, 2003). This study related the high attenuation in the Tyrrhenian mantle wedge above the Adriatic subducting slab to the presence of water in the mantle wedge, because estimated temperatures of the region were well below the values deduced from the Q_P/Q_S values. The hypothesized thermal state corresponds with the ending of magmatic activity in this area at ~0.3 Ma.

Seismic anisotropy

MN data have been used by several authors to describe also the lithospheric and asthenospheric seismic anisotropy properties. Since 1992, with the pioneering work of Vinnik *et al.* (1992), the lattice-preferred orientation of the olivine minerals has been measured in different geodynamic environments, as for example continental mantle and/or tectonically active regions at a global scale. At the beginning of the twenty-first century, several works took advantage of the MN data to focus their attention to the European–Mediterranean region (Fig. 7). In particular, Schmid *et al.* (2004) compared *SKS* and *P* and/or *S* delay times to establish the deformational pattern of the area and to group the results in homogeneous deformational zones, dividing the central Mediterranean in several areas with coherent anisotropic properties and coherent mechanisms of deformation. At the same time, but at a smaller scale, Margheriti *et al.* (2003a) combined data of the temporary and permanent stations to calculate *SKS*-splitting measurements around the Italian peninsula. These results compared to tomographic images and *Pn* maps of the area helped the authors explain and describe the main geodynamic models concerning the Apennines–Tyrrhenian subduction system and its evolution. It is worth to note that in this article the MN stations AQU and VSL, thanks to their long operational time, supported the hypothesis that the complex anisotropic pattern in the upper-mantle structure was due to asthenospheric flows induced by slab rollback and contemporary deformation of the overriding Tyrrhenian plate.

In the first decade of the twenty-first century, MN stations were integrated in several temporary projects designed for a better understanding of the crust and upper-mantle structure beneath the Italian peninsula. Civello and Margheriti (2004) determined the *SKS*-splitting parameters in southern Italy using six MN stations (VAE, AIO, CEL, TIP, CUC, and CLTB). Their study suggested the existence of local scale mantle flow at depths between 100 and 300 km. This flow aligns trench parallel below the Calabrian slab, but rotates to trench normal in the wedge, suggesting asthenospheric circulation around its western edge.

RETREAT (Levin, 2003), Calabria-Apennine-Tyrrhenian Subduction-Collision-Accretion Network (CAT/SCAN) (Steckler *et al.*, 2008; see Data and Resources), and TRANSALP (Kummerow *et al.*, 2004) projects were activated to collect the important seismological pictures of the northern and southern Apennines, and the eastern Alps, respectively. *SKS*-splitting anisotropy distributions from these experiments evidenced as the retreat of the Apennine slab did not produce the same pattern of deformation all along the chain: at south, the mantle deformation process developed completely (Baccheschi *et al.*, 2007, 2008, 2011) with respect to the north, where the presence of the Alpine slab obstructed its flow (Plomerová *et al.*, 2006; Salimbeni *et al.*, 2013). On the other hand, the homogeneous distribution of the fast axes parallel to the chain strike found during the TRANSALP project have been interpreted as due to the presence of an escape flow (in the lower crust and upper mantle) beneath the central and eastern Alps toward the Pannonian basin (Kummerow *et al.*, 2006).

In the western Mediterranean region, data of MN RTC station (Table 1) were used in Salah (2012) to describe the features of the seismic anisotropy in the convergent region between Africa and Iberia; in the eastern part of northern Africa, data recorded at KEG (Kotamya, Egypt) have been used by Margheriti *et al.* (2003b) to interpret the vertical distribution of the anisotropic properties combining RFs and *SKS*-splitting estimations. Recently, Elsheikh (2019), using data recorded at the same station, explained the detected seismic anisotropy pattern as the result of the north-northeast-oriented flow related to the motion and the subduction of the African/Arabian plates beneath Eurasia over the past 150 Ma. Between 2011 and 2015 (Fig. 7), data recorded by BZS, VTS, TIR, KEK, GFA, THL, IDI, ISP, and MALT stations have been analyzed by several authors to define the seismic anisotropic distribution in the southern Apennines and in the Calabrian, Hellenic, and Aegean arcs, and northern Africa (Evangelidis *et al.*, 2011; Baccheschi *et al.*, 2011; Paul *et al.*, 2014; Lemnifi *et al.*, 2015). In addition, Lynner and Long (2013, 2014) used globally distributed seismic data, including data from MN stations IDI and VTS, to constrain the subslab seismic, mantle flow and source-side anisotropy beneath the Caribbean and Scotia, Central America, Alaska–Aleutians, Sumatra, Ryukyu, and Izu–Bonin–Japan–Kurili subduction systems.

Very long-period signals and Earth free oscillations

Some unique information on the inner structure of the Earth can be obtained with the study of the splitting and coupling of the free oscillations. These are the only data that allow to take a direct measurement of the 3D density variation as well as being sensitive to V_P/V_S ratios, that is what is necessary to interpret the tomography anomalies and for deducing the driving forces of the mantle. Free oscillations give the large-scale image of the Earth's interior and are also fundamental to determine the relative rotation rate of the inner core.

Tomographic models that do not include free-oscillation data and/or high-orbit surface waves cannot reconstruct the long-wavelength and largest amplitude structure in the Earth. Free oscillations are then considered complementary to the body-wave datasets used in mantle tomography (Masters *et al.*, 2000). MN data, being recorded by VBB instruments, have always been included in this kind of studies, at global or regional scale. For instance, in Park *et al.* (2008), AQU and VSL recordings of the 2004 Sumatra large earthquake have been compared with the data of the laser extensometers operating in the Gran Sasso underground observatory (central Italy, average 1400 m of rock coverage), to better understand and interpret the signal recorded by these last instruments (Fig. 8).

Future Studies Using Mednet Data

A large number of studies benefit from the long experience gained by 30 yr of activity and data collection of the MN network. The pioneering investment done back to the 1980s to deploy high-quality VBB seismographic stations

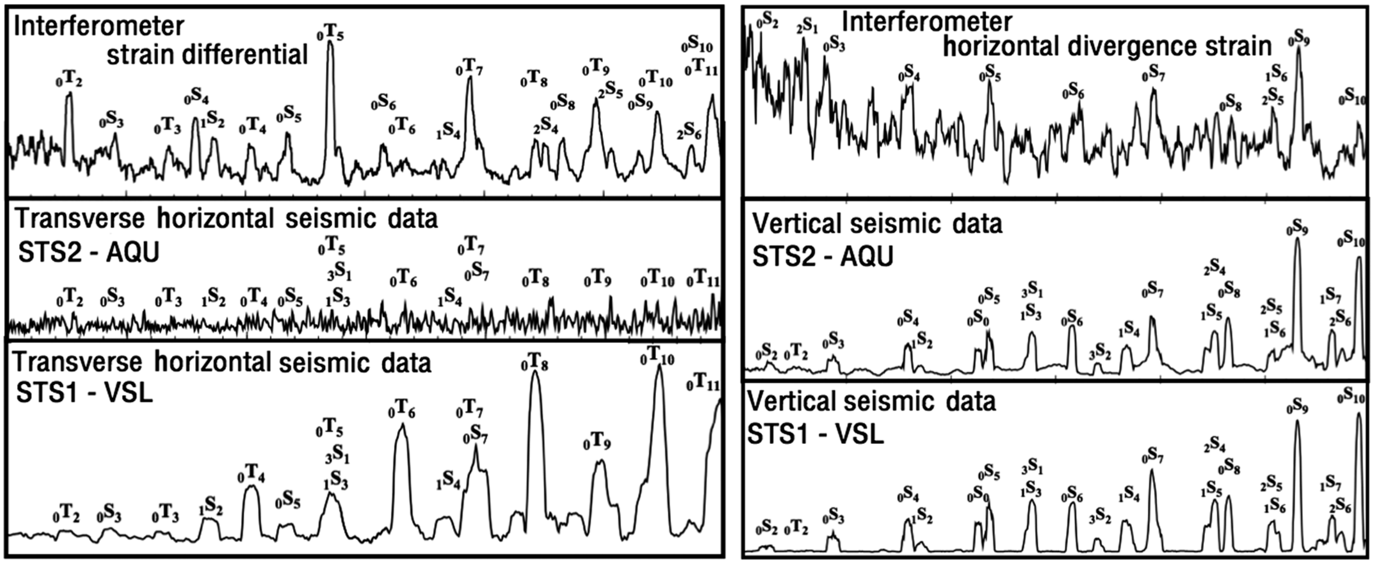


Figure 8. Spectra for the 2004 Sumatra–Andaman earthquake (modified after Park *et al.*, 2008). (Top left) Spectrum estimates of the differential strain along the two orthogonal arms of the strainmeter at Gran Sasso (90 hr record, central Italy). (Lower left) Transverse-horizontal spectra for AQU and VSL stations (90 and 47 hr). (Top right) Spectrum estimates of the divergence strain for a 90 hr record. (Lower right) Vertical spectra for AQU and VSL (both 90 hr record).

has strengthened and supported modern seismological analysis in the Mediterranean region.

Modern techniques allow to automatically compute seismic source parameters using a large number of recordings from BB or VBB stations, spread out around the globe thanks to the real-time availability of the data. The important advantage of VBB sensors with respect to BB seismometers is their ability to record the signal of Earth's tides and free oscillations of the Earth, that is, frequencies around and below 0.001 Hz. At these low frequencies, the VBB are the only sensors that can be used in global seismology studies giving the great opportunity to investigate the deep interior by using the information embedded in the wiggles propagating throughout the Earth beneath the network region (Park *et al.*, 2005; Trnkoczy *et al.*, 2009). The analysis of converted phases as well as complexity in the *P* arrival observed on MN data will allow to shed light on the homogeneity and continuity of the slab at depth and more, in general, to add details on slab structure, as suggested in Di Luccio *et al.* (2016).

Moreover, with modern VBB coupled with high-dynamic-range recording systems, it is possible to record long-period, global, mantle surface waves up to R7, riding on oscillations of solid Earth's tides of longer period, even more than 12 hr. This makes possible to determine the intrinsic frequency-dependent attenuation in the crust and mantle (Lau *et al.*, 2017).

Because of their high dynamic range, the VBB sensors have been applied also in planetary seismometry. For instance, studying the Martian inner structure, Lognonné *et al.* (1996) and Lognonné and Pike (2015) have shown that the instrument that allows to measure tides and seismic signals would have the same resolution in frequency than the STS-2 (flat above 1/120Hz). In conclusion, such ultra-BB seismometer would also allow to measure tidal signals able to shed light on the main features of the Martian crust, mantle, and core (Lognonné and Pike, 2015).

In light of the fact that the Mediterranean basin as well as the Italian peninsula are historically loci of large earthquakes, the availability of high-quality data is the key for sophisticated and modern source and Earth structure wave propagation studies. Although recurrence times of these largest shocks are long, the availability of high dynamic range of VBB sensors would allow the best estimation of energy release, and magnitude computation of those events and consequently the seismic hazard assessment will benefit from their usage.

One of the future applications of MN data could be the rotational seismology. A more complete description of the wavefield generated by a seismic signal can be obtained combining translational signals recorded by VBB sensors, whose linearity is preserved in a wider range of periods with respect to other sensors, with rotational signals. The three components of translational motion and the three components of rotational motion may allow substantial improvements in the studies of velocity heterogeneity, source complexity, and media nonlinearity.

Most observations in the world are carried out only through translational sensors, mainly due to the poor development of rotational sensors compared to translational ones (Lee *et al.*, 2009). In the last two decades, rotational motions from small local earthquakes to large teleseismic and Earth's free oscillations have been recorded successfully by sensitive rotational sensors in several countries (e.g., Salvermoser *et al.*, 2017, and references therein). In light of these studies, each MN VBB sensor could be equipped with a BB rotational sensor so that the analysis of rotational effects from local and regional earthquakes will be a new challenge for the near future.

Data and Resources

MN network information on stations and data recovery reported in this article may be found following the Mediterranean Very Broadband Seismographic Network (MedNet; doi: 10.13127/SD/fBBBtDtd6q). Some plots were made using the Generic Mapping Tools (https://www.generic-mapping-tools.org; Wessel *et al.*, 2019). The other relevant data are from the following sources: Incorporated Research Institutions for Seismology (IRIS), U.S. Geological Survey (USGS) Global Seismographic Network (GSN; doi: 10.7914/SN/IU), GEOSCOPE (doi: 10.18715/GEOSCOPE.G), YELLOWKNIFE Array (doi: 10.7914/SN/CN), GRN (doi: 10.25928/mbx6-hr74), European Integrated Data Archive (EIDA; http://www.orfeus-eu.org/data/eida/; http://terremoti.ingv.it/instruments/network/MN), IRIS (https://www.iris.edu/hq/), Quick Regional Cnetroid Momemt Tensor (QRCMT; http://mednet.rm.ingv.it/quick_rcmt.php), Regional Cnetroid Momemt Tensor (RCMT; http://rcmt2.bo.ingv.it/; doi: 10.13127/rcmt/euromed), Italian Seismic National Network (doi: 10.13127/SD/X0FXnH7QfY), time-domain moment tensor (TDMT; http://terremoti.ingv.it/tdmt), Calabria-Apennine-Tyrrhenian Subduction-Collision-Accretion Network (CAT/SCAN) (https://www.nsf.gov/awardsearch/showAward?AWD_ID=0607687), and QRCMT (http://earthquake.rm.ingv.it/quick.php). All websites were last accessed November 2019. Supplemental material for this article includes the MedNet bibliography that we have collected so far. This list is certainly incomplete, and the reasons for this are explained in its introduction cover page.

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References

Amato, A., L. Margheriti, R. Azzara, A. Basili, C. Chiarabba, M. G. Ciaccio, G. B. Cimini, M. Di Bona, A. Frepoli, F. P. Lucente, *et al.* (1998). Passive seismology and deep structure in central Italy, *Pure Appl. Geophys.* **151,** 479–493.

Arvidsson, R., and G. Ekström (1998). Global CMT analysis of moderate earthquakes $M_w \geq 4.5$ using intermediate-period surface waves, *Bull. Seismol. Soc. Am.* **88,** 1003–1013.

Aster, R., B. Beaudoin, J. Hole, M. Fouch, J. Fowler, and D. James (2005). IRIS Seismology Program marks 20 years of discovery, *Eos Trans. AGU* **86,** no. 17, doi: 10.1029/2005EO170002.

Baccheschi, P., L. Margheriti, and M. S. Steckler (2007). Seismic anisotropy reveals focused mantle flow around the Calabrian slab (Southern Italy), *Geophys. Res. Lett.* **34,** L05302, doi: 10.1029/2006GL028899.

Baccheschi, P., L. Margheriti, M. S. Steckler, and E. Boschi (2011). Anisotropy patterns in the subducting lithosphere and in the mantle wedge: A case study—The southern Italy subduction system, *J. Geophys. Res.* **116,** no. B08306, doi: 10.1029/2010JB007961.

Baccheschi, P., L. Margheriti, M. S. Steckler, and CAT/SCAN Seismology Team (2008). SKS splitting in Southern Italy: Anisotropy variations in a fragmented subduction zone, *Tectonophysics* **462,** nos. 1/4, 49–67, doi: 10.1016/j.tecto.2007.10.014.

Barruol, G., A. Wuestefeld, and G. Bokelmann (2009). *Shear-Wave Splitting in Matlab and SKS Splitting Database*, Université de Montpellier, Laboratoire Géosciences, doi: 10.18715/SKS_SPLITTING_DATABASE.

Beranzoli, L., D. Giardini, and N. A. Pino (1993). Seismogram processing at Mednet, *Comput. Geosci.* **19,** no. 2, 167–174.

Bianchi, I., J. Park, N. Piana Agostinetti, and V. Levin (2010). Mapping seismic anisotropy using harmonic decomposition of receiver functions: An application to Northern Apennines, Italy, *J. Geophys. Res.* **115,** no. B12317, doi: 10.1029/2009JB007061.

Boschi, E., D. Giardini, A. Morelli, G. Romeo, and Q. Taccetti (1988). MedNet—The Italian broad-band seismic network for the Mediterranean, in *Proceedings of Workshop on Broad-Band Downhole Seismometers in the Deep Ocean*, G. M. Purdy and A. M. Dziewonski (Editors), Woods Hole Oceanographic Inst., Massachusetts, 116–124.

Boschi, E., D. Giardini, A. Morelli, G. Romeo, and Q. Taccetti (1991). MedNet: The very broad-band seismic network for the Mediterranean, *Il Nuovo Cimento* **14,** 1–21.

Boschi, L., and G. Ekström (2002). New images of the Earth's upper mantle from measurements of surface wave phase velocity anomalies, *J. Geophys. Res.* **107,** no. B4, doi: 10.1029/2000JB000059.

Castello, B., M. Olivieri, and G. Selvaggi (2007). Local and duration magnitude determination for the Italian earthquake catalog, 1981–2002, *Bull. Seismol. Soc. Am.* **97,** 128–139, doi: 10.1785/0120050258.

Chiaraluce, L., R. Di Stefano, E. Tinti, L. Scognamiglio, M. Michele, E. Casarotti, M. Cattaneo, P. De Gori, C. Chiarabba, G. Monachesi, *et al.* (2017). The 2016 central Italy seismic sequence: A first look at the mainshocks, aftershocks, and source models, *Seismol. Res. Lett.* **88,** no. 3, 757–771, doi: 10.1785/0220160221.

Civello, S., and L. Margheriti (2004). Toroidal mantle flow around the Calabrian slab (Italy) from SKS splitting, *Geophys. Res. Lett.* **31,** L10601, doi: 10.1029/2004GL019607.

Cooley, J. W., and J. W. Tukey (1965). An algorithm for the machine calculation of complex Fourier series, *Math. Comput.* **19,** 297–301.

Di Luccio, F., E. Fukuyama, and N. A. Pino (2005). The 2002 Molise earthquake sequence: What can we learn about the tectonics of southern Italy? *Tectonophysics* **405,** nos. 1/4, 141–154.

Di Luccio, F., P. Persaud, N. A. Pino, R. W. Clayton, D. V. Helmberger, and D. Li (2016). Waveform modeling reveals important features of the subduction zone seismic structure beneath the Tyrrhenian Sea, Italy, *AGU Fall Meeting*, Abstract T51A–2893.

Dziewonski, A. M., T. A. Chou, and J. H. Woodhouse (1981). Determination of earthquake source parameters from waveform data for studies of global and regional seismicity, *J. Geophys. Res.* **86,** 2825–2852.

Ekström, G., A. Morelli, E. Boschi, and A. M. Dziewonski (1998). Moment tensor analysis of the central Italy earthquake sequence of September-October 1997, *Geophys. Res. Lett.* **25,** 1971–1974.

Ekström, G., J. Tromp, and E. W. F. Larson (1997). Measurements and global models of surface wave propagation, *J. Geophys. Res.* **102,** 8137–8158.

Elsheikh, A. A. (2019). Seismic anisotropy and mantle flow beneath East Africa and Arabia, *J. Afr. Earth Sci.* **149,** 97–108, doi: 10.1016/j.jafrearsci.2018.08.002.

Evangelidis, C. P., W.-T. Liang, N. S. Melis, and K. I. Konstantinou (2011). Shear wave anisotropy beneath the Aegean inferred from SKS splitting observations, *J. Geophys. Res.* **116,** no. B04314, doi: 10.1029/2010JB007884.

Ford, H. A., K. M. Fischer, D. L. Abt, C. A. Rychert, and L. T. Elkins-Tanton (2010). The lithosphere-asthenosphere boundary and cratonic lithospheric layering beneath Australia from Sp wave imaging, *Earth Planet. Sci. Lett.* **300,** 299–310.

Fukuyama, E., and D. S. Dreger (2000). Performance test of an automated moment tensor determination system for the future "Tokai" earthquake, *Earth Planets Space* **52,** 383–392.

Giardini, D. (1992). Moment tensor inversion from MedNet data (1) large worldwide earthquakes of 1990, *Geophys. Res. Lett.* **19,** doi: 10.1029/92GL00264.

Giardini, D., and L. Beranzoli (1992). Waveform modelling of the May 20, 1990 Sudan earthquake, *Tectonophysics* **209,** 105–114.

Giardini, D., E. Boschi, S. Mazza, A. Morelli, D. B. Sari, D. Najid, H. Benhallou, M. Bezzeghoud, H. Trabelsi, M. Hfaidh, *et al.* (1992). Very-broad-band seismology in Northern Africa under the MEDNET project, *Tectonophysics* **209,** nos. 1/4, 17–30.

Giardini, D., E. Boschi, and B. Palombo (1993). Moment tensor inversion from MedNet data (2) Regional earthquakes of the Mediterranean, *Geophys. Res. Lett.* **20,** no. 4, 273–276.

Giardini, D., L. Malagnini, B. Palombo, and E. Boschi (1994). Broadband moment tensor inversion from single station, regional surface waves for the 1990, NW-Iran earthquake sequence, *Ann. Geophys.* **37,** no. 6, doi: 10.4401/ag-4157.

Greve, S., H. Paulssen, S. Goes, and M. van Bergen (2014). Shear-velocity structure of the Tyrrhenian Sea: Tectonics, volcanism and mantle (de)hydration of a back-arc basin, *Earth Planet. Sci. Lett.* **400,** 45–53.

Herrmann, R., L. Malagnini, and I. Munafo (2011). Regional moment tensors of the 2009 L'Aquila earthquake sequence, *Bull. Seismol. Soc. Am.* **101,** no. 3, 975–993, doi: 10.1785/0120100184.

Krischer, L., T. Megies, R. Barsch, M. Beyreuther, T. Lecocq, C. Caudron, and J. Wassermann (2015). ObsPy: A bridge for seismology into the scientific Python ecosystem, *Comput. Sci. Discov.* **8,** 014003, doi: 10.1088/1749-4699/8/1/014003.

Kummerow, J., R. Kind, O. Oncken, P. Giese, T. Ryberg, K. Wylegalla, F. Scherbaum, and TRANSALP Working Group (2004). A natural and controlled source seismic profile through the Eastern Alps: TRANSALP, *Earth Planet Sci. Lett.* **225,** 115–129, doi: 10.1016/j.epsl.2004.05.040.

Kummerow, J., R. Kind, and TRANSALP Working Group (2006). Shear wave splitting in the Eastern Alps observed at the TRANSALP network, *Tectonophysics* **414,** 117–125, doi: 10.1016/j.tecto.2005.10.023.

Lau, H. C. P., J. X. Mitrovica, J. L. Davis, J. Tromp, H. Y. Yang, and D. Al-Attar (2017). Tidal tomography constrains Earth's deep-mantle buoyancy, *Nature* **551,** 321–326, doi: 10.1038/nature24452.

Lay, T., J. Berger, R. Buland, R. Butler, G. Ekström, C. R. Hutt, and B. Romanowicz (2002). *Global Seismic Network Design Goals Update 2002*, IRIS, Washington, D.C.

Lee, W. H. K., H. Igel, and M. D. Trifunac (2009). Recent advances in rotational seismology, *Seismol. Res. Lett.* **80,** no. 3, 479–490, doi: 10.1785/gssrl.80.3.479.

Lemnifi, A. A., K. H. Liu, S. S. Gao, C. A. Reed, A. A. Elsheikh, Y. Yu, and A. A. Elmelade (2015). Azimuthal anisotropy beneath north central Africa from shear wave splitting analyses, *Geochem. Geophys. Geosys.* **16,** 1105–1114, doi: 10.1002/2014GC005706.

Levin, V. (2003). Retreating-trench, extension, and accretion tectonics: A multidisciplinary study of the Northern Apennines, *International Federation of Digital Seismograph Networks, Dataset/Seismic Network*, doi: 10.7914/SN/YI_2003.

Li, D., D. Helmberger, R. W. Clayton, and D. Sun (2014). Global synthetic seismograms using a 2-D finite-difference method, *Geophys. J. Int.* **197,** doi: 10.1093/gji/ggu050.

Li, H., F. Bernardi, and A. Michelini (2010). Surface wave dispersion measurements from ambient seismic noise analysis in Italy, *Geophys. J. Int.* **180,** no. 3, 1242–1252, doi: 10.1111/j.1365-246X.2009.04476.x.

Lognonné, P., and W. Pike (2015). Planetary seismometry, in *Extraterrestrial Seismology*, Tong V. C. H. and García R. A. (Editors), Chapter 3, Cambridge University Press, doi: 10.1017/CBO9781107300668.006.

Lognonné, P., J. G. Beyneix, W. B. Banerdt, S. Cache, J. F. Karczewski, and M. Morand (1996). Ultra broad band seismology on InterMarsNet, *Planet. Space Sci.* **44,** no. 11, 1237–1249.

Lynner, C., and M. D. Long (2013). Sub-slab seismic anisotropy and mantle flow beneath the Caribbean and Scotia subduction zones: Effects of slab morphology and kinematics, *Earth Planet. Sci. Lett.* **361,** 367–378, doi: 10.1016/j.epsl.2012.11.007.

Lynner, C., and M. D. Long (2014). Sub-slab anisotropy beneath the Sumatra and circum-Pacific subduction zones from source-side shear wave splitting observations, *Geochem. Geophys. Geosys.* **15,** 2262–2281, doi: 10.1002/2014GC005239.

Margheriti, L., V. Levin, and S. Pondrelli (2003). Vertical distribution of seismic anisotropy beneath the western flank of the Gulf of Suez, *Eos Trans. AGU* **84,** no. 46 (Fall Meet. Suppl.), Abstract S32C–06.

Margheriti, L., F. P. Lucente, and S. Pondrelli (2003). SKS splitting measurements in the Apenninic-Tyrrhenian domain (Italy) and their relation with lithospheric subduction and mantle convection, *J. Geophys. Res.* **108,** no. B2218, doi: 10.1029/2002JB001793.

Margheriti, L., S. Pondrelli, D. Piccinini, N. Piana Agostinetti, L. Giovani, S. Salimbeni, F. P. Lucente, A. Amato, P. Baccheschi, and J. Park (2006). RETREAT seismic deployment in the Northern Apennines, *Ann. Geophys.* **49,** nos. 4/5, 1005–1017.

Marone, F., M. van der Meijde, S. van der Lee, and D. Giardini (2003). Joint inversion of local, regional and teleseismic data for crustal thickness in the Eurasia-Africa plate boundary region, *Geophys. J. Int.* **154,** 499–514.

Masters, G., G. Laske, and F. Gilbert (2000). Matrix autoregressive analysis of free-oscillation coupling and splitting, *Geophys. J. Int.* **143,** 478–489.

Mazza, S., M. Olivieri, A. Mandiello, and P. Casale (2008). The Mediterranean Broad Band Seismographic Network Anno 2005/06, in *Earthquake Monitoring and Seismic Hazard Mitigation in Balkan Countries*, E. S. Husebye (Editor), NATO Science Series: IV: Earth and Environmental Sciences, Vol. 81, Springer, Dordrecht, The Netherlands.

McNamara, D. E., and R. P. Buland (2004). Ambient noise levels in the continental United States, *Bull. Seismol. Soc. Am.* **94,** no. 4, 1517–1527.

Megna, A., and A. Morelli (1994). Determination of Moho depth and dip beneath MedNet station AQU by analysis of broadband receiver functions, *Ann. Geophys.* **XXXVII,** 913–928.

Megna, A., A. Morelli, S. Santini, and F. Vetrano (1995). *Determinazione della struttura della Moho in Sardegna meridionale mediante analisi della funzione di risposta crostale della stazione MedNet VSL*, Gruppo Nazionale di Geofisica della Terra Solida, 117–124 (in Italian).

Mele, G., E. Sandvol, and P. Cavinato (2006). Evidence of crustal thickening beneath the central Apennines (Italy) from teleseismic receiver functions, *Earth Planet. Sci. Lett.* **249,** 425–435.

Melis, N. S., and K. I. Konstantinou (2006). Real-time seismic monitoring in the Greek Region: An example from the 17 October 2005 East Aegean Sea earthquake sequence, *Seismol. Res. Lett.* **77,** no. 3, 364–370.

Miller, M. S., and N. Piana Agostinetti (2012). Insights into the evolution of the Italian lithospheric structure from S receiver function analysis, *Earth Planet. Sci. Lett.* **345/348,** 49–59.

Morelli, A., G. Ekström, and M. Olivieri (2000). Source properties of the 1997-1998 Central Italy earthquake sequence from inversion of long period and broadband seismograms, *J. Seismol.* **4,** 365–375.

Ohtake, M., and Y. Ishikawa (1995). Seismic observation networks in Japan, *J. Phys. Earth* **43,** 563–584.

Örgülü, G. (2011). Seismicity and source parameters for small-scale earthquakes along the splays of the North Anatolian Fault (NAF) in the Marmara Sea, *Geophys. J. Int.* **184,** 385–404, doi: 10.1111/j.1365-246X.2010.04844.x.

Park, J., A. Amoruso, L. Crescentini, and E. Boschi (2008). Long-period toroidal earth free oscillations from the great Sumatra–Andaman earthquake observed by paired laser extensometers in Gran Sasso, Italy, *Geophys. J. Int.* **173,** 887–905, doi: 10.1111/j.1365-246X.2008.03769.x.

Park, J., R. Butler, K. Anderson, J. Berger, H. Benz, P. Davis, C. R. Hutt, C. S. McCreery, T. Ahern, G. Ekström, *et al.* (2005). Performance review of the Global Seismographic Network for the 26 December 2004 Sumatra-Andaman megathrust earthquake, *Seismol. Res. Lett.* **76,** 329–340, doi: 10.1785/gssrl.76.3.331.

Pasyanos, M., E. Matzel, W. Walter, and A. Rodgers (2009). Broadband Lg attenuation modelling in the Middle East, *Geophys. J. Int.* **177,** 1166–1176, doi: 10.1111/j.1365-246X.2009.04128.x.

Paul, A., H. Karabulut, A. K. Mutlu, and G. Salaun (2014). A comprehensive and densely sampled map of shear-wave azimuthal anisotropy in the Aegean-Anatolia region, *Earth Planet. Sci. Lett.* **389,** 14–22, doi: 10.1016/j.epsl.2013.12.019.

Piccinini, D., M. Di Bona, F. P. Lucente, V. Levin, and J. Park (2010). Seismic attenuation and mantle wedge temperature in the northern Apennines subduction zone (Italy) from teleseismic body wave spectra, *J. Geophys. Res.* **115,** no. B09309, doi: 10.1029/2009JB007180.

Pino, N. A., and F. Di Luccio (2009). Source complexity of the 6 April 2009 L'Aquila (central Italy) earthquake and its strongest aftershock revealed by elementary seismological analysis, *Geophys. Res. Lett.* **36,** no. 23, doi: 10.1029/2009GL041331.

Pino, N. A., S. Mazza, and E. Boschi (1999). Rupture directivity of the major shocks in the 1997 Umbria-Marche (central Italy) sequence from regional broadband waveforms, *Geophys. Res. Lett.* **26,** no. 14, 2101–2104.

Piromallo, C., and A. Morelli (2003). P wave tomography of the mantle under the Alpine-Mediterranean area, *J. Geophys. Res.* **108,** doi: 10.1029/2002JB001757.

Plomerová, J., L. Margheriti, J. Park, V. Babuska, S. Pondrelli, L. Vecsey, D. Piccinini, V. Levin, P. Baccheschi, and S. Salimbeni (2006). Seismic anisotropy beneath the Northern Apennines (Italy): Mantle flow or lithosphere fabric? *Earth Planet. Sci. Lett.* **247,** 157–170, doi: 10.1016/j.epsl.2006.04.023.

Pondrelli, S., and S. Salimbeni (2015). Regional moment tensor review: An example from the European–Mediterranean region, in *Encyclopedia of Earthquake Engineering*, M. Beer, I. Kougioumtzoglou, E. Patelli, and I. K. Au (Editors), Springer, Berlin/Heidelberg, Germany.

Pondrelli, S., A. Morelli, and G. Ekström (2004). European-Mediterranean regional centroid moment tensor catalog: Solutions for years 2001 and 2002, *Phys. Earth Planet. In.* **145,** nos. 1/4, 127–147.

Pondrelli, S., A. Morelli, G. Ekström, S. Mazza, E. Boschi, and A. M. Dziewonski (2002). European-Mediterranean regional centroid-moment tensors: 1997-2000, *Phys. Earth Planet. In.* **130,** 71–101.

Pondrelli, S., S. Salimbeni, G. Ekström, A. Morelli, P. Gasperini, and G. Vannucci (2006). The Italian CMT dataset from 1977 to the present, *Phys. Earth Planet. In.* **159,** nos. 3/4, 286–303, doi: 10.1016/j.pepi.2006.07.008.

Pondrelli, S., S. Salimbeni, A. Morelli, G. Ekström, and E. Boschi (2007). European-Mediterranean regional centroid moment tensor catalog: Solutions for years 2003 and 2004, *Phys. Earth Planet. In.* **164,** nos. 1/2, 90–112.

Pondrelli, S., S. Salimbeni, A. Morelli, G. Ekström, L. Postpischl, G. Vannucci, and E. Boschi (2011). European-Mediterranean regional centroid moment tensor catalog: Solutions for 2005-2008, *Phys. Earth Planet. In.* **185,** no. 3, 74–81.

Roult, G., J.-P. Montagner, B. A. Romanowicz, M. Cara, D. Rouland, R. Pillet, J.-F. Karczewski, L. Rivera, E. Stutzmann, A. Maggi, *et al.* (2010). The GEOSCOPE Program: Progress and challenges during the past 30 years, *Seismol. Res. Lett.* **81,** no. 3, 427–452.

Roumelioti, Z., C. Benetatos, and A. Kiratzi (2009). The 14 February 2008 earthquake (M6.7) sequence offshore south Peloponnese

(Greece): Source models of the three strongest events, *Tectonophys.* **471,** 272–284.

Salah, M. K. (2012). A seismological evidence for the northwestward movement of Africa with respect to Iberia from shear wave splitting, *Geosci. Front.* **3,** no. 5, 681–696, doi: 10.1016/j.gsf.2012.01.005.

Salimbeni, S., S. Pondrelli, and L. Margheriti (2013). Hints on the deformation penetration induced by subductions and collision processes: Seismic anisotropy beneath the Adria region (Central Mediterranean), *J. Geophys. Res.* **118,** 5814–5826, doi: 10.1002/2013JB010253.

Salvermoser, J., C. Hadziioannou, S. Hable, L. Krischer, B. Chow, C. Ramos, J. Wassermann, U. Schreiber, A. Gebauer, and H. Igel (2017). An event database for rotational seismology, *Seismol. Res. Lett.* **88,** no. 3, 935–941.

Schmid, C., S. van der Lee, and D. Giardini (2004). Delay times and shear-wave splitting in the Mediterranean region, *Geophys. J. Int.* **159,** 275–290.

Scognamiglio, L., L. Margheriti, F. M. Mele, E. Tinti, A. Bono, P. De Gori, V. Lauciani, F. P. Lucente, A. G. Mandiello, C. Marcocci, *et al.* (2012). The 2012 Pianura Padana Emiliana seismic sequence: Locations, moment tensors and magnitudes, *Ann. Geophys.* **55,** no. 4, 549–559, doi: 10.4401/ag-6159.

Scognamiglio, L., E. Tinti, and A. Michelini (2009). Real-time determination of seismic moment tensor for Italian region, *Bull. Seismol. Soc. Am.* **99,** no. 4, 2223–2242, doi: 10.1785/0120080104.

Scognamiglio, L., E. Tinti, A. Michelini, D. S. Dreger, A. Cirella, M. Cocco, S. Mazza, and A. Piatanesi (2010). Fast determination of moment tensors and rupture history: What has been learned from the 6 April 2009 L'Aquila earthquake sequence, *Seismol. Res. Lett.* **81,** no. 6, 892–906, doi: 10.1785/gssrl.81.6.892.

Scognamiglio, L., E. Tinti, and M. Quintiliani (2016). The first month of the 2016 Central Italy seismic sequence: Fast determination of time domain moment tensors and finite fault model analysis of the M_L 5.4 aftershock, *Ann. Geophys.* **59,** no. 5, doi: 10.4401/ag-7246.

Sipkin, S. (1986). Estimation of earthquake source parameters by the inversion of waveform data: Global seismicity, 1981-1983, *Bull. Seismol. Soc. Am.* **76,** 1515–1541.

Steckler, M. S., N. Piana Agostinetti, C. K. Wilson, P. Roselli, L. Seeber, A. Amato, and A. Lerner-Lam (2008). Crustal structure in the Southern Apennines from teleseismic receiver functions, *Geology* **36,** no. 2, 155–158, doi: 10.1130/G24065A.1.

Thio, H. K., X. Song, C. Saikia, and D. Helmberger (1999). Seismic source and structure estimation in the western Mediterranean using a sparse broadband network, *J. Geophys. Res.* **104,** no. B1, 845–861.

Tinti, E., L. Scognamiglio, A. Cirella, and M. Cocco (2014). Up-dip directivity in near-source during the 2009 L'Aquila mainshock, *Geophys. J. Int.* **198,** 1618–1631.

Trnkoczy, A., J. Havskov, and L. Ottemller (2009). Seismic Networks, Chapter 8, in *New Manual of Seismological Observatory Practice (NMSOP)*, P. Bormann (Editor), GeoForschungsZentrum (GFZ), Potsdam, Germany, 1–60, doi: 10.2312/GFZ.NMSOP_r1_ch8.

Valleé, M., and F. Di Luccio (2005). Source analysis of the 2002 Molise, southern Italy, twin earthquakes (10/31 and 11/01), *Geophys. Res. Lett.* **32,** L12309, doi: 10.1029/2005GL022687.

van der Meijde, M., S. van der Lee, and D. Giardini (2003). Crustal structure beneath broad-band seismic stations in the Mediterranean region, *Geophys. J. Int.* **152,** 729–739.

Vinnik, L. P., L. I. Makeyeva, A. Milev, and A. Y. Usenko (1992). Global patterns of azimuthal anisotropy and deformations in the continental mantle, *Geophys. J. Int.* **111,** no. 3, 433–447, doi: 10.1111/j.1365-246X.1992.tb02102.x.

Walter, R. W., K. Mayeda, L. Malagnini, and L. Scognamiglio (2007). Regional body-wave attenuation using a coda source normalization method: Application to MedNet records of earthquakes in Italy, *Geophys. Res. Lett.* **34,** L10308, doi: 10.1029/2007GL029990.

Webb, S. C. (2002). Seismic noise on land and on the sea floor, in *Int. Hand-book on Earthquake and Engineering Seismology*, W. H. K. Lee, H. Kanamori, P. C. Jennings, and C. Kisslinger (Editors), Part A, Chapter 19, Academic Press, Amsterdam, The Netherlands, 305–318.

Wessel, P., J. Luis, L. Uieda, R. Scharroo, F. Wobbe, W. H. F. Smith, and D. Tian (2019). The Generic Mapping Tools Version 6, *Geochem. Geophys. Geosys.* **20,** doi: 10.1029/2019GC008515.

Wielandt, E. (2002). Seismometry, in *International Handbook of Earthquake and Engineering Seismology*, W. H. K. Lee, H. Kanamori, P. C. Jennings, and C. Kisslinger (Editors), Part A, Academic Press, 283–304, ISBN: 0-12-440652-1.

Wielandt, E., and J. M. Steim (1986). A digital very-broad-band seismograph, *Ann. Geophys.* **4,** no. 3, 227–232.

Wielandt, E., and G. Streckeisen (1982). The leaf-spring seismometer—Design and performance, *Bull. Seismol. Soc. Am.* **72,** 2349–2367.

Wüstefeld, A., G. Bokelmann, C. Zaroli, and G. Barruol (2008). SplitLab: A shear-wave splitting environment in Matlab, *Comput. Geosci.* **34,** no. 5, 515–528, doi: 10.1016/j.cageo.2007.08.002.

Zaccarelli, L., N. M. Shapiro, L. Faenza, G. Soldati, and A. Michelini (2011). Variations of crustal elastic properties during the 2009 L'Aquila earthquake inferred from cross-correlations of ambient seismic noise, *Geophy. Res. Lett.* **38,** L24304, doi: 10.1029/2011GL049750.

Zhu, H., E. Bozdag, and J. Tromp (2012). Structure of the European upper mantle revealed by adjoint tomography, *Nature Geosci.* **5,** 493–498.

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