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The Hellenic Seismological Network of Crete (HSNC): validation and results of the 2013 aftershock sequences

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Abstract. The last century, the global urbanization has leaded the majority of population to move into big, metropolitan areas. Small areas on the Earth's surface are being built with tall buildings in areas close to seismogenic zones. Such an area of great importance is the Hellenic arc in Greece. Among the regions with high seismicity is Crete, located on the subduction zone of the Eastern Mediterranean plate underneath the Aegean plate. The Hellenic Seismological Network of Crete (HSNC) has been built to cover the need on continuous monitoring of the regional seismicity in the vicinity of the South Aegean Sea and Crete Island. In the present work, with the use of Z-map software the spatial variability of Magnitude of Completeness (Mc) is calculated from HSNC's manual analysis catalogue of events from the beginning of 2008 till the end of September 2015, supporting the good coverage of HSNC in the area surrounding Crete Island. Furthermore, we discuss the 2013 seismicity when two large earthquakes occurred in the vicinity of Crete Island. The two main shocks and their aftershock sequences have been relocated with the use of HYPOINVERSE earthquake location software. Finally, the quality of seismological stations is addressed using the standard PQLX software.

1 Introduction

The number and quality of seismological networks in Europe has increased in the past decades. Nevertheless, the need for localized networks monitoring in areas of great seismic and scientific interest is constant. A very active seismic area is the Hellenic arc, located at the eastern part of Mediterranean Sea, in companion with a volcanic arc created by the subduction of the tectonic plates (McKenzie, 1972). The convergence of the Eastern Mediterranean plate and the Aegean plate at $4\,\mathrm{cm\,yr^{-1}}$ rate creates a complex tectonic environment (Le Pichon and Angelier, 1979). In this area, more than 60 % of the total seismic energy in Europe is being released with magnitudes up to 8.3 (Papazachos, 1990). The subduction of the Mediterranean plate under the Aegean plate creates the Benioff zone of intermediate and depth earthquakes, as it has been estimated by seismological studies (McKenzie, 1972; Le Pichon and Angelier, 1979) and it has been revealed by tomographic results (Spakman, 1988; Papazachos and Nolet, 1997).

The Hellenic Seismological Network of Crete (HSNC) is a local seismological network covering and supporting the continuous need for monitoring of the front of Hellenic Arc, with its official operation started in 2004. Within almost a decade of operation, the existence of HSNC supports the application and test of modern techniques as that of earthquake early warning (Hloupis and Vallianatos, 2013, 2015). In 2013, two large earthquakes occurred in the vicinity of Crete Island. The HSNC identified more than 510 and 360 aftershocks respectively followed after the main event. The two main shocks and their aftershock sequences have been located with a GUI program that use the HYPO earthquake location software (Lee and Lahr, 1972) and relocated with HYPOINVERSE (Klein, 2002) and a modified crust model. In the present work in order to present the everyday results and to give evidence of the contribution of HSNC in the effort of creation reliable data sets, we show the preliminary results from the analysis of two aftershock sequences. In addition, the magnitude of completeness of the HSNC covered area (i.e. in the front oh Hellenic Arc) and the distribution of Power Spectral Density of HSNC's seismological stations, provide elements related with the operation of HSNC in one of the most scientifically important areas in Europe as the front of the Hellenic Arc is.

2 The development of the Hellenic Seismological Network of Crete

The HSNC started its first operation in 2004 with 4 Guralp CMG-40T 1 s sensors with flat response to velocity from 1 to 100 Hz installed in each major city of Crete. Within a period less than a decade (2004–2012) it expands to 12 online stations. Some of the initial locations of the first 6 stations were changed to more suitable locations. At the same time few of Guralp CMG-40T 1 s sensors were installed have been substituted with Guralp CMG ESPC 60 and 120 s (Hloupis et al., 2013), which are flat to velocity from 100 Hz to 0.016 Hz (60 s) and 0.0083 Hz (120 s). The next two years, three more short period sensors were upgraded with broadband. At the same time two new stations added to the seismic network to provide better coverage area. In middle of 2015 two more short period seismometers have been changed with broadband, leaving only 1 short period station in network, which will be uprated in the near future. All stations, since the network's first operation, were equipped with Reftek 130-01 digitizers (www.trimble.com/). In the beginning the digitizers continuously record data at 125 Hz, this number reduced to 100 Hz in the end of 2013 due to large amount of data stored after the network's expansion. Communication with the central station is established by using private wired ADSL MPLS VPN lines, satellite lines, and RF. The HSNC has its own private satellite hub allowing single-hop communication between central station and VSATs (Hloupis et al., 2013). Data collection is achieved using commercial RTP software (www.reftek.com). All stations are registered to International Seismological Centre (ISC) and the network is listed by International Federation of Digital Seismograph Networks (FDSN) with the assigned permanent network code HC.

The HSNC operates continuously collecting data from its 14 stations (see Fig. 1 and Table 1 for details) and 10 more stations from neighboring networks. By the of the end of 2013 the HSNC has bilateral agreements with national Observatory of Athens (NOA) (http://www.gein.noa.gr/en/), Aristotle University of Thessaloniki (AUTH) (http://geophysics.geo.auth.gr/the_seisnet/WEBSITE_2005/station_index_en.html) and Kandili Observatory and Earthquake Research Institution (KOERI) (http://www.koeri.boun.edu.tr/) ensuring a constant exchange of data. Data from neighboring networks are fed to RTP using sl2rtpd protocol transforming mini-SEED data to raw PASSCAL format. For automatic processing of seismic signal, we employ three Earthquake Monitoring Systems (EMS): Seismic Network Data Protocol (Synapse Seismic Center, Russia), SeisComp3 (Deutsches GeoForschungsZentrum, Germany) and Earthworm (USGS, USA) that run independently and in parallel. Each of the first 2 EMS is assigned for specific area monitoring and the third one is used supplementary to increase the sensitivity of the network. The Earthworm monitoring system is calibrated to work better in identifying events close to Crete region while SeisComp3 is best used for locating earthquakes in the broader area. All EMS create automated bulletins which are being distributed to registered users and authorities. In addition manual analysis of seismic events is being conducted and event messages are sent to registered users and authorities. A dedicated webpage is being updated after every event, presenting the spatial distribution of the 30 last manual located events (http://gaia.chania.teicrete.gr/uk/?cat=11). The complete catalogue of seismic events is available under request.

Table 1. Code names (as registered at ISC) and coordinates for the HSNC seismological stations.

Code	Location	Longitude	Latitude	Altitude (m)
KNDR	Koundoura	23.6248	35.2348	13.5
FRMA	Ferma	25.8555	35.0187	21.5
CHAN	Chania	24.0429	35.5193	36.0
KSTL	Kasteli	25.3374	35.2092	335.0
HRKL	Herakleio	25.1015	35.2115	81.0
PRNS	Prines	24.4260	35.3450	325.0
KTHR	Kythira	22.9938	36.2447	270.0
TMBK	Tymbaki	24.7662	35.0724	12.0
STIA	Siteia	26.0909	35.2021	93.0
KOSK	Kos	26.9785	36.7516	10.0
KLMT	Kalamata	22.0597	37.0613	6.0
THT2	Santorini	25.4218	36.4351	24.0
RODP	Rodopos	23.7577	35.5604	308.0
GVDS	Gavdos	24.0585	34.8389	348.0

3 Coverage of HSNC – Quality of Stations

The spatial variability of Magnitude of Completeness (Mc) is calculated from HSNC's manual analysis catalogue of events with the use of Z-map software (http://www.seismo.ethz.ch/prod/software/zmap/index_EN) for the period of 2008 until the end of September, 2015. As indicated by Gutenberg–Richter distribution (Gutenberg and Richter, 1936) Magnitude of Completeness denotes the minimum magnitude of an earthquake, which a network can detect within the boundaries of a given region. Calculation of Mc is done using the "best combination" option of Z-map which compares the Maximum Curvature Technique (Wyss et al., 1999) and the Goodness-of-Fit Test (Wiemer and Wyss, 2000). The Mc estimation methods are based on the validity of Gutenberg–Richter Law (Mignan and Woessner, 2012). Figure 2 illustrates a map with the distribution of Mc for HSNC. The Mc value at the close vicinity of Crete Island is down to 2.0 at the western part, between 2 to 2.7 at the central and southern part of the island, and down to 3.0 at the eastern part of the coverage area. The present results regarding the HSNC magnitude of completeness map are comparable with that presented for the NOA-HUSN catalogue using both the Bayesian magni-

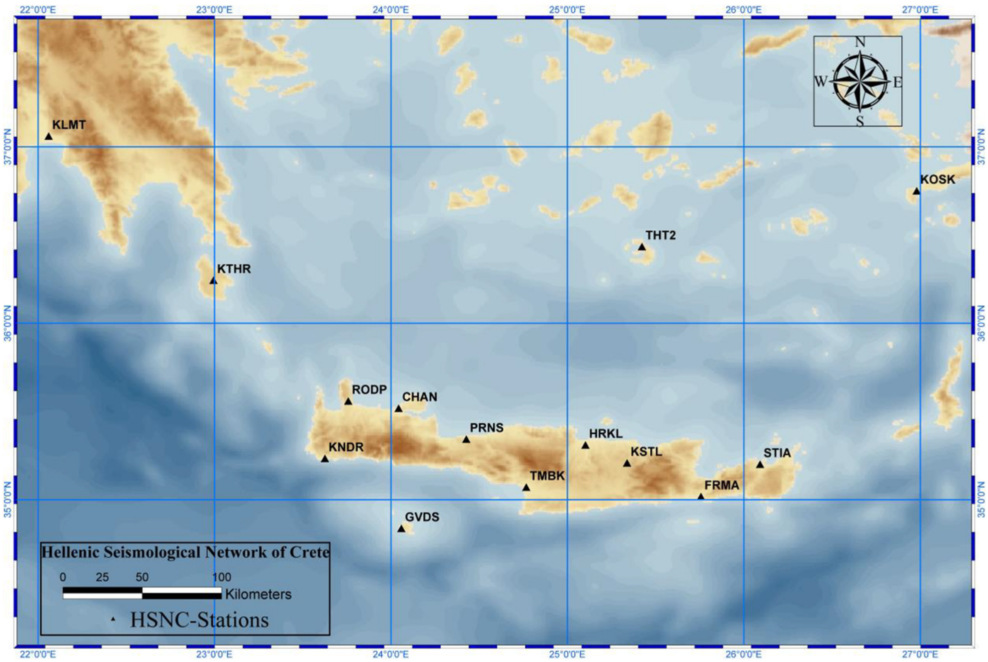

Figure 1. The HSNC seismological stations location on the front of Hellenic Arc (Crete and South Aegean region).

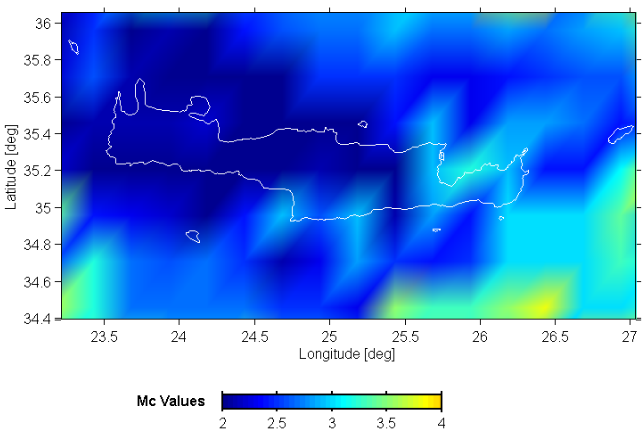

Figure 2. Magnitude of Completeness for HSNC station distribution, using the manual catalogue of the HSNC from 2008 until end of October 2015 (for details see text).

tude of completeness and the frequency -magnitude distribution (Mignan and Chouliaras, 2014).

The HSNC operation time is relative small compared to other networks in Greece. Therefore an effort to evaluate the operation results is done by comparing the magnitudes of 1500 events located by the 2 largest networks of Greece the NOA and AUTH. The common identified events, in origin time and location are from manual catalogs from 2014 to middle of 2015 for the broader area of Crete. The results illustrated on Fig. 3 suggest that the HSNC reporting magnitudes are slightly larger than the other two networks report.

To present the quality of stations deployed from the HSNC network, we use the PQLX software (McNamara and Boaz, 2005) to analyze the time series collected. PQLX calculates the distribution of Power Spectral Density (PSD) of seismological waveform with the use of a probability density function (PDF), and is considered as the standard way of presenting the quality of seismological stations. In this work, we are presenting three stations of the HSNC network, FRMA, STIA and CHAN which are located at the, eastern and western part of Crete Island (Fig. 4). The noise level at long periods is caused due to the fact that the stations of HSNC are located near urban zones. In the future the noisy stations are going to move in quieter locations. PQLX uses the whole recordings (noise and events) to calculate the PDF. System transients (cultural noise) map into a low-level background probability while ambient noise conditions reveal themselves as high probability occurrences. Cultural noise propagates mainly as high-frequency surface waves (> 1–10 Hz) that attenuate within several kilometers in distance and depth. Cultural noise shows very strong diurnal variations and has characteristic frequencies depending on the source of the disturbance. On the other hand, large teleseismic earthquakes can produce powers above ambient noise levels across the entire spectrum and are dominated by surface waves > 10 s, while small events dominate the short period, < 1 s. This presentation allows for the overall estimation of station quality and a baseline level of earth noise at each site (McNamara and Boaz, 2005).

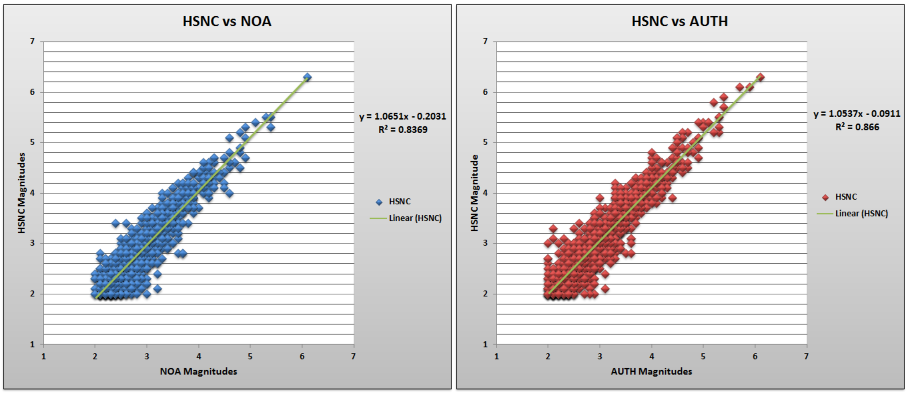

Figure 3. Comparison of the magnitudes reported by HSNC and that of NOA and AUTH. The events are from manual catalogs from 2014 to middle of 2015. The slope of the fitting show that HSNC is calculating the event magnitudes slightly higher.

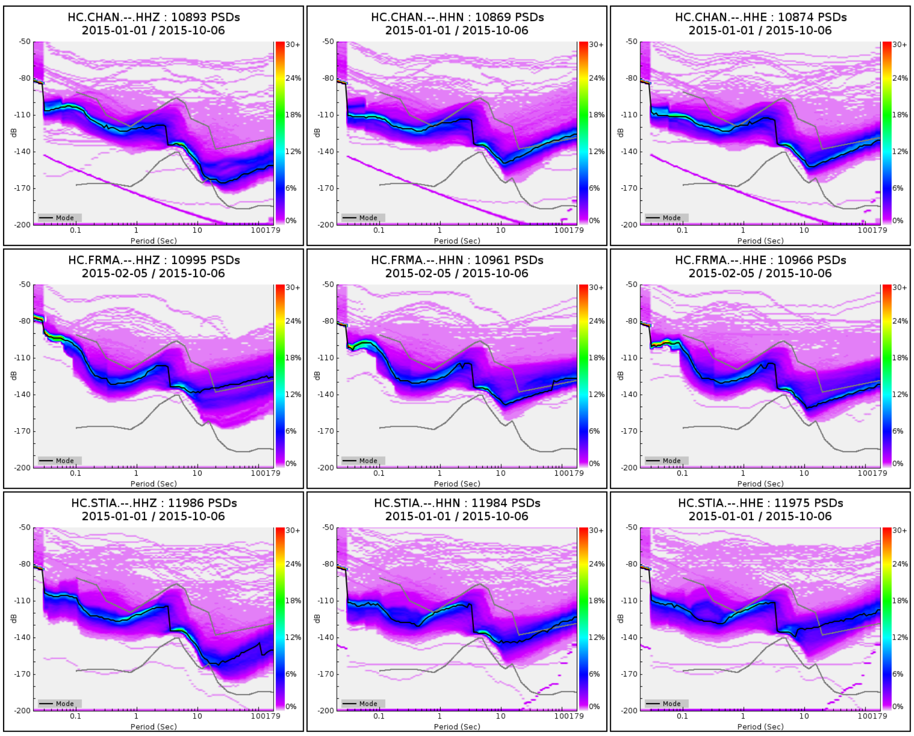

Figure 4. Distribution of Power Spectral Density for stations FRMA, KSTL and STIA of the HSNC network using Power Density Function, created using PQLX software.

4 The aftershock sequences

Within 2013, one of the seismically active periods in the front of Hellenic Arc two strong earthquakes with magnitude greater or equal to 6.0 occurred in the vicinity of Crete Island. Both mainshocks were felt in the whole Crete region. The initial almost real time location procedure has been done with the use of a dedicated software which is been adopted by the early stages of HSNC operation. The software is user friendly for picking phases and runs HYPO software but its main disadvantage is that it uses binary files with a generic crust model which is not suitable for the area. The Hellenic front arc is the initial part from the Eurasian – African subduction zone. The amphitheatric shape, created by the lithospheric plates convergence, is has been characterized by different geological environments along the arc. Therefore a generic crust model cannot be used in such a complicated structure. In order to properly relocate the aftershock sequences, we modified the Meier et al. (2004) crust models (Table 2) for both sequences (V. Karakostas, personal communication, 2014). The first results of this effort are presented in the vertical to fault plane cross sections in Fig. 5 for the 15 June 2013

Table 2. The crust models used for 15 June 2013 and 12 October 2013 relocations.

Depth (km)	Velocity *P* (km s^{-1})	Depth (km)	Velocity *P* (km s^{-1})
0.0	4.60	0.0	4.20
1.0	5.40	1.0	5.70
2.5	5.70	3.0	6.30
5.0	6.00	8.0	6.40
8.0	6.10	12.0	6.45
11.0	6.20	20.0	6.50
15.0	6.30	25.0	6.80
20.0	6.60	30.0	7.30
25.0	7.00	33.0	7.90
30.0	7.50	–	–
33.0	8.00	–	–

Table 3. The 5 strongest event errors in the determinations of the epicenters in the horizontal and vertical dimensions for the 15 June 2013 and 12 October 2013 sequnces.

Day	Hour	Magnitude	Residual	ERH	ERZ
15/06/2013	16:11:01	6	0.13	2.8	1.4
13/06/2013	21:39:04	5.8	0.22	2.9	1.5
13/06/2013	21:43:16	4.9	0.32	0.9	0.9
15/06/2013	17:22:06	4.8	0.26	0.7	0.8
19/06/2013	19:05:09	4.8	0.2	0.7	0.5
12/10/2013	13:11:53	6.2	0.16	0.8	1.3
13/10/2013	17:43:52	4.1	0.16	0.7	1
12/10/2013	13:17:00	4	0.16	0.7	1.1
12/10/2013	14:05:50	4	0.16	0.7	1
19/10/2013	2:19:21	3.9	0.15	0.7	1.1

event and in Fig. 6 for the 12 October 2013 event. Additionally the process errors, in horizontal and vertical dimension for five strongest events for each sequence are illustrated in Table 3. For the station time error calibration file, which is needed by HYPOINVERSE software, only large aftershocks recordings with many *P* and *S* phases (more than 21) have been used. Other important criteria for selecting the aftershocks were to be recorded in most of available stations in epicentral distances approximately less than 200 km, marked phases having very small errors in time, depth and azimuth. Parameters such as distance and RMS residual weighting also were considered. The most of the aftershock events of the 15th June sequence were recorded by 11 stations with code names: TMBK, STIA, KSTL, FRMA, ZKR, PRNS, RODP, KNDR, GVDS, HRKL and CHAN. Likewise the 12 October sequence were recorded on the following 10 stations: KTHR, VLI, CHAN, KNDR, RODP, PRNS, MHLO, HRKL, KRND and GVDS. For clarity we note that the data received from the stations VLI, MHLO and ZKR belongs to NOA and the KRND belongs to AUTH. These data contributed in the relocation procedure by providing more seismic wave phases. The results of the strong earthquakes and

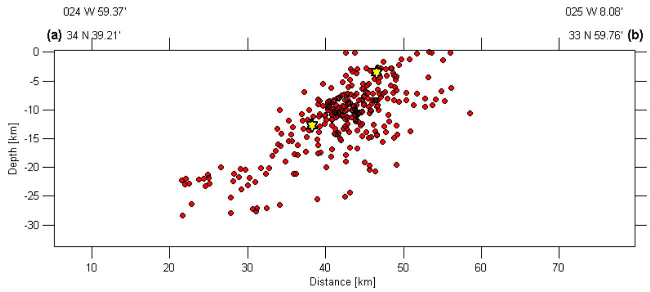

Figure 5. Cross section of the aftershock seismicity of the 15 June event. The yellow stars are the strong and the moderate events and with red circles are the aftershocks.

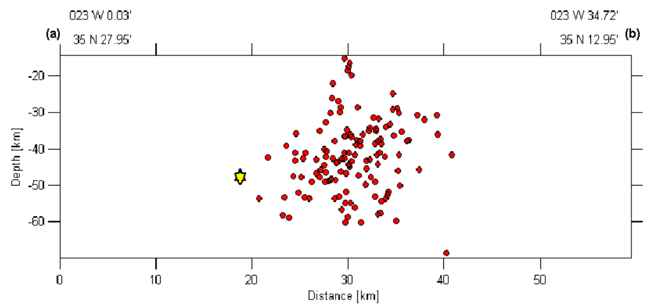

Figure 6. Cross section of the aftershock seismicity of the 12 October 2013 event. The yellow star is the strong event and with red circles are the aftershocks.

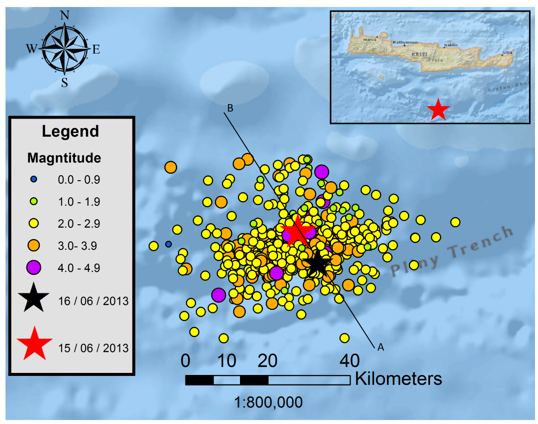

Figure 7. The 15 June 2013 Mainshock and the distribution of the aftershocks after the relocation process (see text). The two strong shocks are denoted with red and black star. The aftershocks' magnitude is represented with circles with different color and size.

their aftershock are presented as an evidence of the monitoring capability of Hellenic Arc Front. Therefore the information that is provided and ploted is limited and related to seismic network operation. All the identified aftershock with minimum of 15 or more phases were used in relocation process. The available events near the fault area of the mains event considered as aftershocks. The end time for each se-

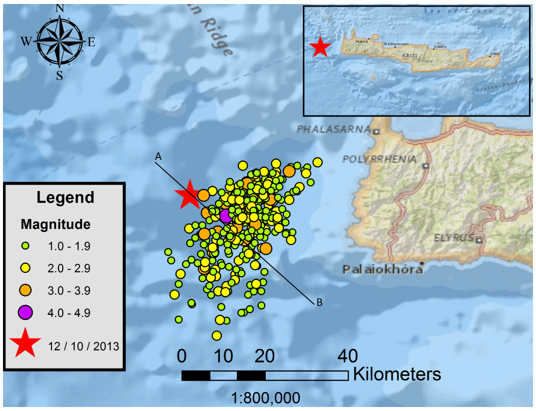

Figure 8. The 12 October 2013 Mainshock and the distribution of the aftershock after the relocation process (see text). The strong shock is denoted with red star. The aftershocks' magnitude is represented with circles with different color and size.

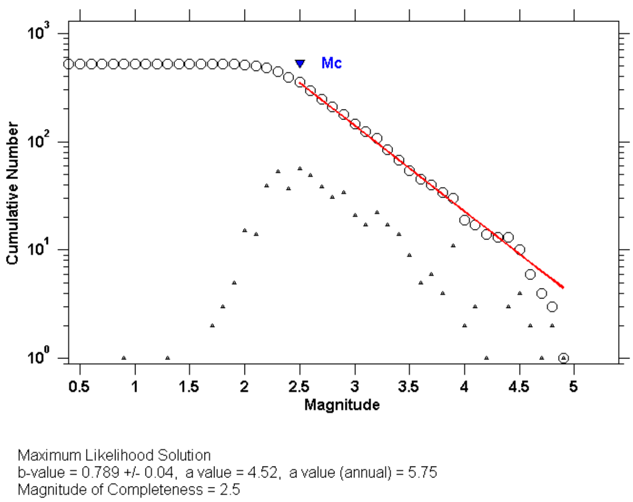

Figure 9. The Mmin, *a* and *b* values for the 15 June 2013 aftershock sequence (see text for details).

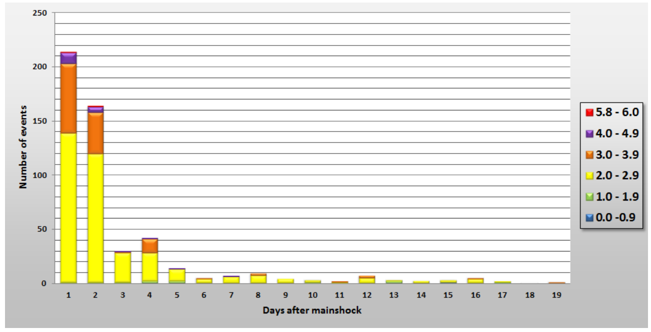

Figure 10. The daily rate of aftershocks and its magnitudes after the strong shock of the 15 June 2013.

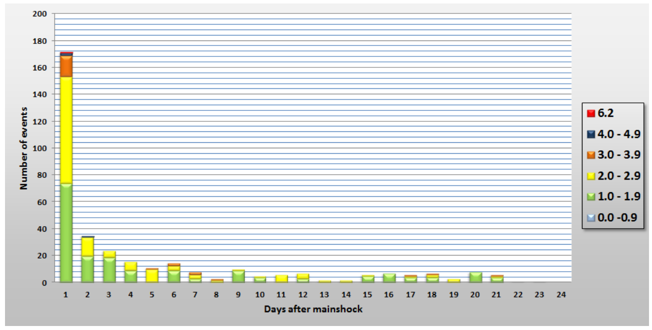

Figure 11. The daily rate of aftershocks and its magnitudes after the strong shock of the 12 October 2013.

quence was considered a time period of 48 h or more with no earthquakes above the Mmin in the fault area. The results of the two relocations are illustrated for 15 June in Fig. 7 and for 12 October Fig. 8 respectively.

The first strong event took place on 15 June 2013 at 16:11 UTC in the front of the Hellenic Arc, south from central Crete (Latitude = 34.31, Longitude = 25.04). The magnitude and depth of the mainshock are $M_w = 6.0$ and 15 km respectively. A second moderate activation occurred after approximately 29 h with magnitude $M_w = 5.8$ and depth 6.5 km. The use "best combination" option of Z-map for the whole aftershock sequence provided the Gutenberg–Richter distribution, calculated the *b* values 0.789, the a value 4.52 and the Mmin 2.5 (Fig. 9). The moment magnitude for the strong and moderate events was calculated with Seisan (ftp://ftp.geo.uib.no/pub/seismo/SOFTWARE/SEISAN/) software by analyzing the spectral displacement, the stress drop and other parameters of seismic wave spectrum. The mainshock was followed for more than 510 recorded aftershocks span in a time period about 17 days. In Fig. 10 the daily rate of events after the mainshock is presented as well as the magnitude of these events. The time period between the strong and the moderate event more than 230 aftershocks occurred with the magnitude range to vary from micro (1.9–2.9) to light (4.1–4.8) with a considerable amount of events in minor range (3.0–3.9). Few hours after the moderate $M_w = 5.8$ activation the rate of aftershocks decrease drastically, since about 280 aftershocks followed this second event in a time period about 15 days. As Fig. 10 shows there was a high seismic energy release within the first two days with most of the events having minor to light magnitudes. The rest period there is a low seismic release rate observed which leads to the conclusion that the aftershock sequence decay rate was fast.

The second strong event presented on 12 October 2013 at the western part of Crete (Latitude = 35.39, Longitude = 23.26). We note that this event has attracted the interest due to the number of different foreshocks observed (Vallianatos et al., 2014; Contadakis et al., 2015). The magnitude of the mainshock are $M_w = 6.2$ in a depth of 47 km. The mainshock was followed by more than 360 recorded af-

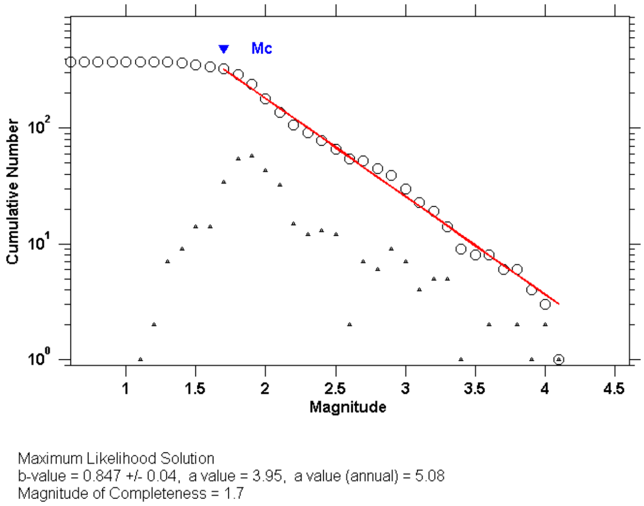

Figure 12. The Mmin, a and b values for the 12 October 2013 aftershock sequence (see text).

tershocks in a time window of 23 days. In Fig. 11 the daily rate of events after the mainshock is presented as well as the magnitude of these events. With the use "best combination" option of Z-map the b values calculated 0.847, as well as the a value 3.95 and the Mmin 1.7 (Fig. 12). The majority of the aftershocks were identified the first day with most of them with magnitudes range between micro and minor (range 1.1 to 3.9) and only three light events (range 4.0 to 4.1). The depth of the mainshock was probably the reason for the limited number of aftershock events and the low magnitudes observed, compared to 15 June 2013 event. It is noticeable that only the first day there was a considerable amount of seismic energy released and after that the aftershock activity is pretty low.

5 Conclusions

In order to cover the need for a reliable and modern monitoring of the seismic activity around Crete Island, Greece, the HSNC started its operations in 2004. The goal was to provide a continuous coverage at the front of the Hellenic arc and to permit the study of new methods as that of earthquake early warning (Hloupis and Vallianatos, 2013, 2015). Currently having 13 online broadband stations and one short period, the HSNC is being in constant explanations acts, as a complete observation unit able to continuous monitor the seismic activity within a very sensitive area in the East Mediterranean as that in the South of the Hellenic Arc. Using three different and independent EMS ensures a triple check on the data, enabling different triggering algorithms to be applied. As an example the earthquake events and the results of the analyses of the 2 large earthquake sequences in 2013 indicates the importance of the HSNC network and its capability to contribute in the detailed monitoring of the seismic activity over the subduction zone in the Hellenic Arc.

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