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Quarry blasts, underwater explosions, and other dubious seismic events in NE Italy from 1977 to 2013

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ABSTRACT We have re-examined the phase readings of the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS) seismometric database, in the years 1977-2013, to isolate explosions and undefined events marked with peculiar codes and clearly tracked in the original full printouts of paper bulletins. Nowadays this tag is not easily available in online metadata, thus leading to erroneous interpretations of the seismicity patterns. We also performed a specific analysis on quarry blasts reported to the Geological Survey of the Trento Autonomous Province, and detected by the network in 2013. More than 4,400 events constitute a new prototypal database of artificial/dubious earthquakes, potentially ascribed to anthropogenic or "induced" events; about 40% of them may be located with the standard procedures of OGS bulletins, even if some solutions are of bad quality. More than 1,000 events, which mainly occurred during the first decades of the monitoring of the north-eastern Alps and reported in actual bulletins, have to be removed from data analysis of natural seismicity, and are easily traceable with the tool given as Supplementary Material.

Key words: non-tectonic earthquakes, northern Italy, OGS earthquake database

1. Introduction

The increasing number of seismometric stations and the betterment in modern digital monitoring systems have enormously increased the number of detected earthquakes all over the world, thus lowering the magnitude of completeness (M_c), i.e., the energy/distance threshold below which events should have been omitted from an earthquake catalogue. Despite its conceptual simplicity, the evaluation of local M_c is not trivial and its variations in space and time are detectable with difficulty; they are masked by several natural, technological, and human factors, such as the fluctuations of seismicity rates, background noise (anthropogenic, meteorological, but also due to nearby or distant seismic sequences), the evolution of the seismometric networks, the individual functioning of each station and protocol in data transfer, and the training and renewal of personnel in seismology laboratories. Recent literature partially accounts for these problems in countries with a long history of instrumental recording (e.g., Mignan and Woessner, 2012 and references therein).

When the M_c threshold reaches values below the perception thresholds, such as about M_L=2.5-2.8, very local seismic events are detected, and anthropogenic disturbances or events with non-tectonic origin contaminate the seismicity picture. The discrimination between natural and artificial events is often difficult; usually it is not accomplished by routine analyses performed by national or regional networks.

Among "fake" earthquakes, quarry blasts are probably the most frequent shaking events erroneously reported in local earthquake bulletins. Part of the energy released by quarry explosions propagates beyond the rupture volume as elastic waves, just like with natural earthquakes. One feature usually assumed for explosions is low energy. As a consequence, if the overall network sensitivity allows the detection of low magnitude events, human activities such as those of quarry extraction can become relevant in contaminating the resulting earthquake catalogues, concealing the natural pattern of micro-seismicity (Wiemer and Baer, 2000; Cattaneo *et al.*, 2014).

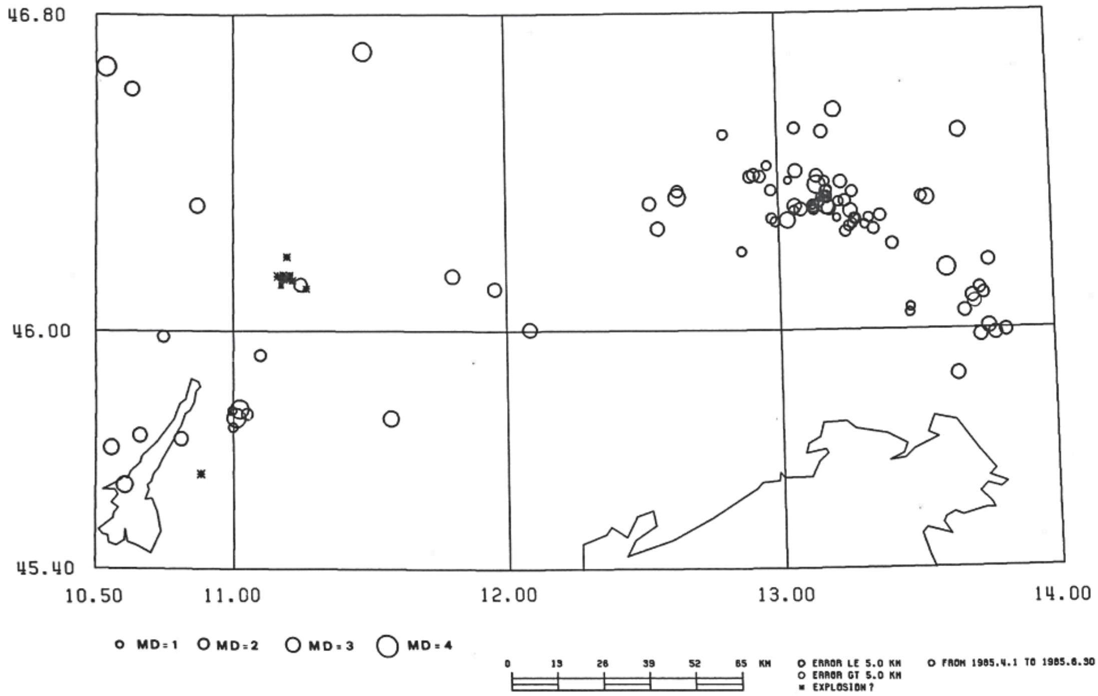
In north-eastern Italy, the first part of a regional seismometric network was inaugurated in 1977, a year after the devastating M_L 6.4 earthquake that struck the Friuli Venezia Giulia (FVG) region, causing about 1,000 casualties (Slejko *et al.*, 1999; Aoudia *et al.*, 2000). The network was built and has been managed by the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS), and it has progressively increased the monitoring capability from the pioneer Trieste WWSSN station (Morelli, 1959; Sandron *et al.*, 2014), to today's networks, which have transnational capabilities (Bragato *et al.*, 2013a); such networks are operated by the OGS department Centro Ricerche Sismologiche (CRS), both for study and civil protection alert purposes, mainly at the request of regional authorities (for more details, refer to Priolo *et al.*, 2005; Bragato *et al.*, 2011). Periodic bulletins of regional earthquakes have been compiled according to the dissemination strategies of the time (OGS, 1977-1981, 1982-1990, 1991-2013); since 1991 on-line bulletins have been available, with phase readings, location lists, static maps, and statistics (http://www.crs.inogs.it/bollettino/RSFVG/); dynamic representations of real-time data and past seismicity have been available on a website dedicated to real-time seismology (http://rts.crs.inogs.it/) since 2009. A dedicated waveform archive has been implemented in the last years, too (Priolo *et al.*, 2011; http://oasis.crs.inogs.it). All these functionalities broaden NE Italy's seismometrical monitoring capabilities in comparison with the ones provided by the Italian National Seismic Network [managed by Istituto Nazionale di Geofisica e di Vulcanologia (INGV)] and foreign agencies. The events located by OGS in its region of authority are from twice to five times more than the ones reported in the national ISIDe database (ISIDe Working Group INGV, 2010), as schematically reported in Table 1; these numbers clearly state a different completeness magnitude for the two agencies, not easily comparable as different rules for computing magnitude are used.

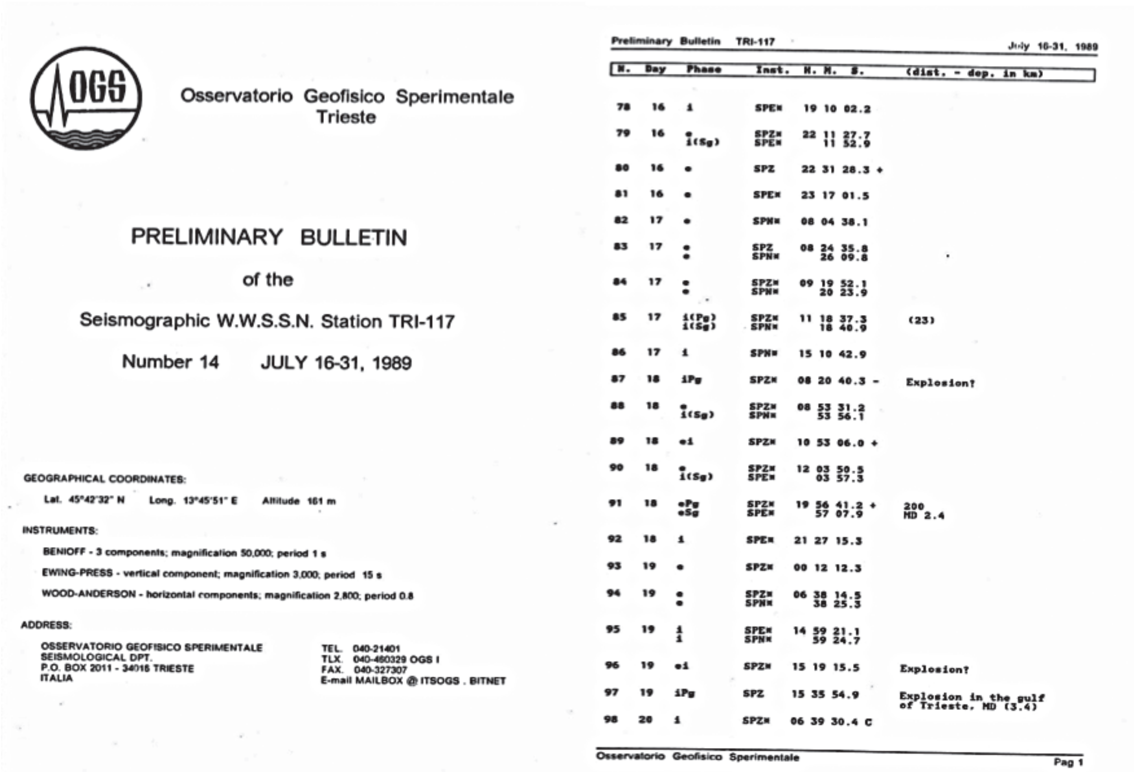
Table 1 - Number of earthquakes reported in the OGS and INGV bulletins, for a rectangular area in north-eastern Italy (latitude 45°-47°N, longitude 11°-14°E): the search has been performed using the functionalities provided by the databases (at http://rts.crs.inogs.it/en/search/advancedsearch.html for OGS bulletins; at http://iside.rm.ingv.it/iside/standard/result.jsp?rst=1&page=EVENTS for INGV ones) in seven time frames, with no magnitude and depth thresholds; mislocation problems may affect the Emilia 2012 events as reported in the preliminary OGS bulletins.

	REFERENCE PERIOD	NUMBER OF EVENTS IN OGS DATA SET	NUMBER OF EVENTS IN INGV DATA SET	EVENTS RATIO
1	1980-01-01/1984-12-31	4050	Not available	
2	1985-01-01/1989-12-31	2430	442	5.5
3	1990-01-01/1994-12-31	928	199	4.7
4	1995-01-01/1999-12-31	1836	378	4.9
5	2000-01-01/2004-12-31	1510	288	5.2
6	2005-01-01/2009-12-31	1436	525	2.7
7	2010-01-01/2014-12-31	5029	928	5.4

Since the beginning of regional monitoring, OGS personnel have been trained to recognize and pick up the P and S phases of local earthquakes; alphanumeric codes have been introduced in the pickings data set to mark peculiar cases referring to distant or dubious events (e.g., “T”=teleseism, “E”=explosion, “U”=undefined event). By working on analogue paper recordings and doing the manual phase readings at one station a time, the analysts were used to exclude the picking of waveforms whose signals could be clearly assigned to an anthropogenic origin or explosions, and to read the phases of dubious events especially if they were detectable at more than one station. The identification of non-tectonic earthquakes such as quarry explosions is not a trivial issue (e.g., Kulhànek, 1990); in the early times of OGS instrumental seismology, it was based essentially on space-time considerations (e.g., inventory of the quarry activities of the region, consistency of origin time with working hours) and signal feature (e.g., lack or very uncertain recognition of S phases, similarities in traces at the same stations); sometimes notifications of explosions are given by local authorities (e.g., in the case of detonation of war bombs) and reported in local newspapers, too. Dubious events recognised at several stations enabled their standard processing to obtain a hypocentral location (see Fig. 1). Since 1977, several changes have occurred in network geometry and instrumentation. In 1981, some stations were added to the westernmost end of the FVG network, thus initiating earthquake detection in a less seismic area [Trento (TN) Autonomous Province] with intense quarries activities; also, some stations were managed by different organizations, some personnel changed, and the dissemination of bulletins changed too, according to new technological resources and strategies. All this has led to a heterogeneous utilization of “E” and “U” codes during the network lifetime, and sometimes the traceability of fake/anthropogenic or dubious events in the online release of catalogues has been lost.

In this study we re-examine all the P and S phases originally marked with “E” and “U” codes in the actual OGS bulletin data picks and archives; we analyse the space and time distribution of located and non-located events, to recognise and isolate them from the original data set. Such events constitute a prototypal catalogue of artificial/dubious earthquakes, potentially ascribed to the type of “induced” events, that have occurred in NE Italy from 1977 to 2013. As the Trentino Porphyry Quarry District represents more than 60% of these events, a specific analysis is performed on the most recent waveform data; a time-space selection based on the explosion time records marks some





OGS

Osservatorio Geofisico Sperimentale
Trieste

PRELIMINARY BULLETIN

of the

Seismographic W.W.S.S.N. Station TRI-117

Number 14 JULY 16-31, 1989

GEOGRAPHICAL COORDINATES:

Lat. 45°42'32" N Long. 13°45'51" E Altitude 161 m

INSTRUMENTS:

BENIOFF - 3 components; magnification 50,000; period 1 s

EWING-PRESS - vertical component; magnification 3,000; period 15 s

WOOD-ANDERSON - horizontal components; magnification 2,800; period 0.8

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Preliminary Bulletin TRI-117 July 16-31, 1989

N.	Day	Phase	Inst.	H. M. S.	(dist. - dep. in km)
78	16	i	SPE*	19 10 02.2	
79	16	e i(Sg)	SPZ* SPE*	22 11 27.7 11 52.9	
80	16	e	SPZ	22 31 28.3 +	
81	16	e	SPE*	23 17 01.5	
82	17	e	SPN*	08 04 38.1	
83	17	e e	SPZ SPN*	08 24 35.8 26 09.8	
84	17	e e	SPZ* SPN*	09 19 52.1 20 23.9	
85	17	i(Pg) i(Sg)	SPZ* SPN*	11 18 37.3 18 40.9	(23)
86	17	i	SPN*	15 10 42.9	
87	18	iPg	SPZ*	08 20 40.3 -	Explosion?
88	18	e i(Sg)	SPZ* SPN*	08 53 31.2 53 56.1	
89	18	ei	SPZ*	10 53 06.0 +	
90	18	e i(Sg)	SPZ* SPE*	12 03 50.5 03 57.3	
91	18	ePg eSg	SPZ* SPE*	19 56 41.2 + 57 07.9	200 MD 2.4
92	18	i	SPE*	21 27 15.3	
93	19	e	SPZ*	00 12 12.3	
94	19	e e	SPZ* SPN*	06 38 14.5 38 25.3	
95	19	i i	SPE* SPN*	14 59 21.1 59 24.7	
96	19	ei	SPZ*	15 19 15.5	Explosion?
97	19	iPg	SPZ	15 35 54.9	Explosion in the gulf of Trieste. MD (3.4)
98	20	i	SPZ*	06 39 30.4 C	

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Fig. 1 - Explosion data as reported in the original bulletins on paper: a) in the quarterly OGS bulletin in 1985, earthquakes are plotted by circles, and potential explosions by stars; b) in the biweekly preliminary bulletin of the WWSSN Station TRI-117 in 1989, dubious phases with comments notified by the maritime authorities.

phase picks; the identified events represent a high-quality learning set that can be used in the future for explosion recognition, based on fully automatic waveform cross-correlation.

By removing explosions and dubious events from the online OGS catalogue, we delete some peculiar patterns in earthquake distribution that do not belong to the natural seismicity of the north-eastern Alps and surrounding areas.

2. The OGS seismometric network

OGS has a long tradition in seismometric monitoring (Gentili *et al.*, 2011). In 1912, a 1000 kg Wiechert seismograph was installed in the Maritime Observatory of Trieste, at that time part of the Austrian Empire. As an Italian seismological station, Trieste dates back to 1931 (Morelli, 1959), and it became a station of the World-Wide Standardized Seismographic Network (WWSSN) in 1963. After the earthquakes that struck the FVG region in 1976, a permanent regional seismic network was installed in north-eastern Italy by OGS; it has been operating continuously since May 6, 1977 (Renner, 1995; Priolo *et al.*, 2005; Bragato *et al.*, 2013a).

At the beginning of the network's evolution, nine Mark LC4-1D geophones were installed in the epicentral area of the 1976 earthquakes; later, during 1982-1983, the sensors were replaced by Willmore MKIIIA seismometres and the network was expanded to 11 stations. In the same years, OGS started managing six stations of the TN seismic network. The TN seismic network became independent in 1990, operated by personnel of the Geological Survey of the TN Autonomous Province; OGS continued monitoring mainly in the FVG area with gradual extension into the Veneto (VE) region. In 2000, most of the stations were equipped with Lennartz LE-3DLite seismometres, and the network reached a nearly stable configuration. Since 1995, the short-period network has been incrementally expanded with broadband seismic stations. At present, the broadband network includes 20 stations, mainly owned by OGS: a few stations are owned by the Civil Protection authority of FVG and of VE, and two are co-owned with the University of Trieste. The broadband stations are fully operated by OGS, except for the two stations of AGOR and FERB, which are operated in collaboration with the INGV. Since 2008, OGS has again been fully in charge of seismic monitoring of the TN region. With regard to the evolution of the real-time alarm system, it should be mentioned that an automatic H-24 service has been active since 1994. Until 2007, it was based only on short-period stations as triggering stations; from 2008 on, OGS broadband stations and those managed by other institutions have been gradually added into the automatic alarm system provided to the Regional Civil Protection authorities of FVG, TN, and VE.

With the aim of increasing the quality of earthquake location in NE Italy, picks data from other Italian and international institutions have been always used, taken from authoritative bulletins; from 1991 to 2007, picks from the TN stations were inserted in the OGS bulletins, and routinely used for locating earthquakes mainly in the VE region (Bragato, pers. comm.). Data exchanges in real time have been active since the early 2000s, with the Environmental Agency of the Republic of Slovenia [Agencija Republike Slovenije za Okolje (ARSO)], the Austrian Central Institute for Meteorology and Geodynamics [Zentralanstalt für Meteorologie und Geodynamik (ZAMG)], lately with the Bolzano (BZ) Autonomous Province and INGV; since the beginning of 2014, OGS personnel have performed original phase readings on waveforms provided by other agencies, too, for earthquakes inside its monitoring region.

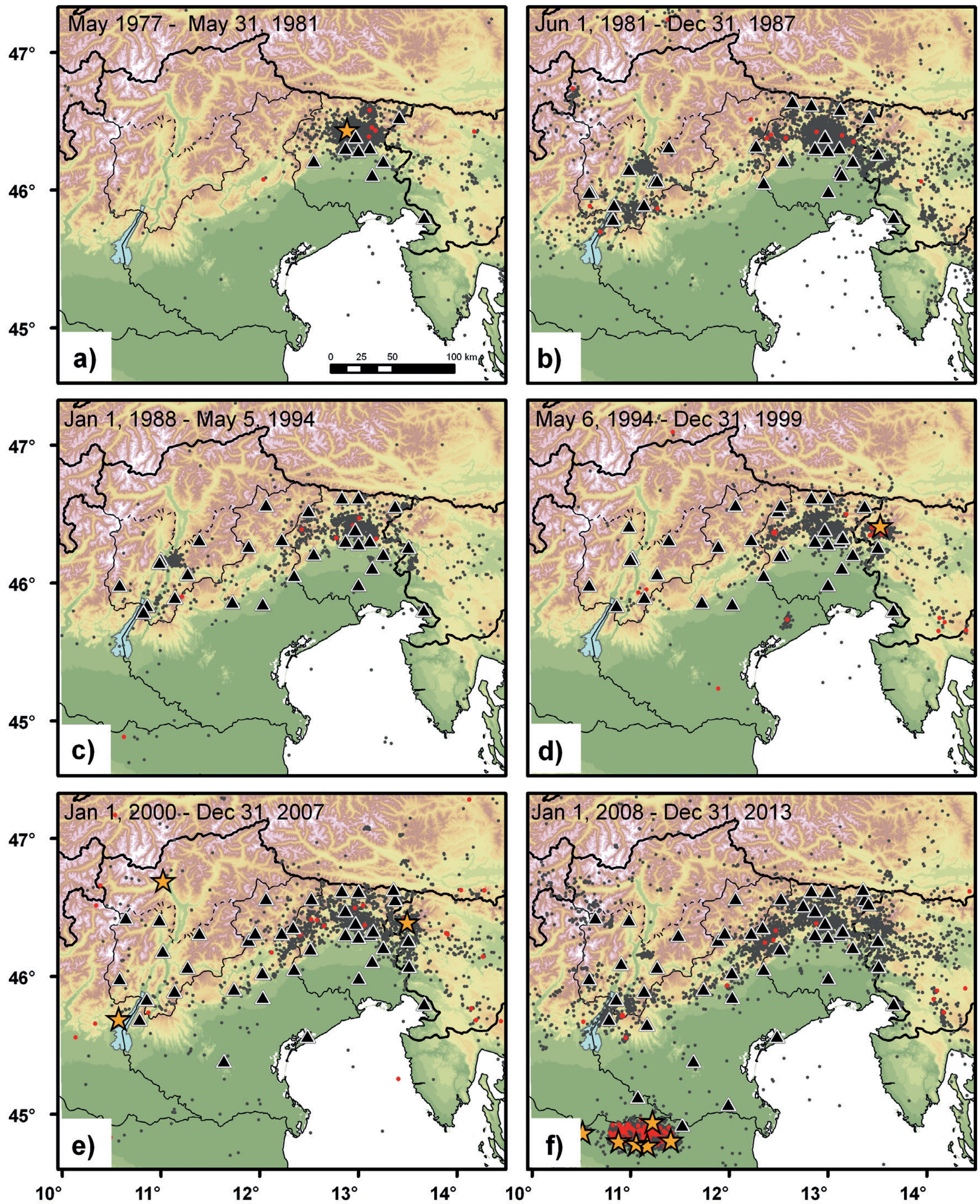


Fig. 2 - Network geometries and seismicity distribution in time. Gray dots mark earthquakes with M_D<3.5, red ones for 3.5≤M_D<5.0, yellow stars for events with M_D5.0. Black triangles indicate seismic stations active during the time frame; a) and b) analogue period, the number of stations gradually increased to cover both FVG and TN regions (TN stations since 1981); c) first digital period, triggering stations changed in time (in 1990, TN stations became independent); d) change in the acquisition system and data storage of the second digital period; e) and f) time frame corresponding to a more stable network configuration, and enhancement of station sensors and quality controls. See text for details.

Fig. 2 shows the main changes in network geometry with snapshots of the seismicity that occurred in six time frames; the actual configuration of the network, site locations, and technical characteristics are available at the real-time website (http://rts.crs.inogs.it). The alert system provides automatic preliminary location and magnitude determination for the region of north-eastern Italy, which are communicated to the regional authorities with fax/sms/email notifications in less than 2 minutes, on average, from origin time. Real-time data are promptly available on the website, too, in the format of automatic solutions or data revised by seismologists. Major earthquakes (yellow stars in Fig. 2) extracted from OGS archives are listed in Table 2; due to the huge number of events that occurred in 2012 with the Emilia earthquake sequence [see for example: Saraò and Peruzza, (2012), Barnaba *et al.*, (2014), and Govoni *et al.*, (2014)], the 2012 and 2013 bulletins are preliminary as they are still going through data integration and refinements.

So far, we subdivide the evolution of the network roughly into five main periods, characterized by different triggering conditions, seismic acquisition systems, and/or instrumental characteristics [see Gentili *et al.*, (2011), for details]:

- May 6, 1977 - December 31, 1987 (Figs. 2a and 2b): recordings of analogue data in continuous mode;
- January 1, 1988 - May 5, 1994 (Fig. 2c): change from analogue to digital acquisition system (Earth Data 9690), simultaneous triggering condition on at least three stations for permanent data storage;
- May 6, 1994 - December 31, 1999 (Fig. 2d): change of the digital acquisition system to Lennartz Mars 88 equipment, permanent data storage of all triggered signals;
- January 1, 2000 - December 31, 2007 (Fig. 2e): triggering conditions and acquisition data system as above with a general improvement of the network performance, expanding the station number and using broadband signals, too;
- January 1, 2008 - December 31, 2013 (Fig. 2f): during this period, the acquisition data system and the automatic alarm system are based on the ANTELOPE software.

Table 2 - List of the major events ($M_L \geq 5.0$) reported in OGS bulletins (the years 2012 and 2013 are still preliminary).

ID_LINK	DATE	LAT (°)	LON (°)	M_L	LOCATION
1977_00342	1977-09-16 23:48:06	46.3700	13.0160	5.2	Tolmezzo, Friuli
1979_00171	1979-02-06 09:49:47	47.4470	14.9240	5.1	Mt. Vordernberg, Austria
1998_00282	1998-04-12 10:55:32	46.3240	13.6780	5.6	Kobarid, Slovenia
2001_00566	2001-07-17 15:06:15	46.6800	11.0980	5.2	Merano, Alto Adige
2003_00788	2003-09-14 21:42:53	44.2660	11.5080	5.0	Fontanelice, Emilia
2004_00392	2004-07-12 13:04:06	46.3050	13.6400	5.1	Kobarid, Slovenia
2004_02392	2004-11-24 22:59:40	45.6850	10.6020	5.1	Gargnano, Lombardia
2008_01201	2008-12-23 15:24:20	44.5310	10.2230	5.5	Neviano D. Arduini, Emilia
2008_01226	2008-12-23 21:58:26	44.5270	10.3970	5.1	Rossena, Emilia
2011_00846	2011-07-17 18:30:27	44.9290	11.2390	5.0	S. Martino in Spino, Emilia
2012_00080	2012-01-25 08:06:36	44.8610	10.5220	5.0	Brescello, Emilia
2012_00456	2012-05-20 02:03:50	44.7600	11.1790	5.9	Camposanto, Emilia
2012_00562	2012-05-20 13:18:02	44.7890	11.4200	5.1	S. Agostino, Romagna
2012_00900	2012-05-29 07:00:01	44.7730	11.0670	5.8	S. Prospero, Emilia
2012_00939	2012-05-29 10:55:55	44.7940	10.8880	5.5	Carpi, Emilia
2013_71448	2013-01-25 14:48:17	44.1285	10.2650	5.1	2 km NW of Vagli Sotto (Lucca)
2013_74340	2013-06-21 10:33:56	44.0927	10.0910	5.6	4 km E of Ortonovo (La Spezia)

Fig. 3 - Phase readings in time at the stations managed by OGS in FVG, VE, and TN regions (the last inside the red rectangle). They represent indirectly the operational status and sensitivity of the stations. The gap for all the stations in 1991 is due to a fire accident at the acquisition centre in the Udine castle, and the move to the current location (Udine). Some stations have been affected by problems of signal transmission, or local disturbances.

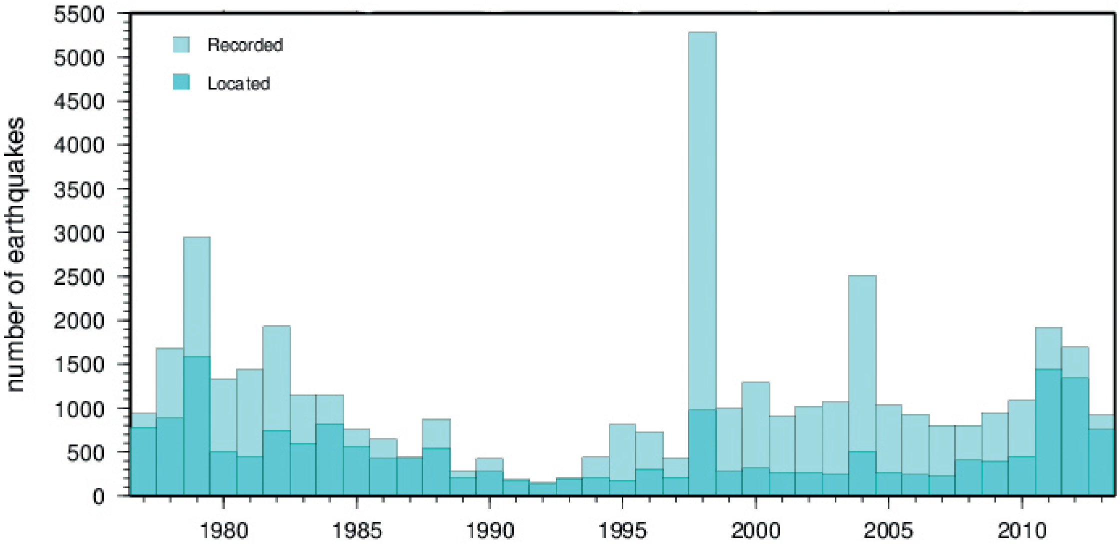


Fig. 4 - Annual number of earthquakes recorded and located by the OGS North-eastern Seismometric Network.

The main changes in network geometry, i.e., the ON/OFF status of instrumented sites, are given in the original printed OGS bulletins and unpublished reports delivered to the regional authorities; nevertheless, minor changes in station functionality, instrumentation, and sometimes also site characteristics and location may be untracked, or kept off the records. A general overview of available data was compiled by Gentili *et al*., (2011), for the time period 1977-2007, and it was based on inter-arrival times of phase picks between events. Fig. 3 refines these data and updates them up to December 2013, by showing the operational status of the FVG, TN, and VE networks directly based on available phase readings data uploaded in the archives.

Note the gradual increase in the number of stations in the FVG area, and the decommissioning or discontinuos functioning of some stations in VE until 2006. The changes for the TN stations since 1990, the year in which separate management of the TN network began, are not a measure of their effective functioning, as TN data have been merged in the OGS bulletins only if they refer to events with regional relevance, identified by the FVG and VE networks, too.

In Fig. 4, a global counting of located and not located events reported in OGS bulletins is given on annual basis. Note the fluctuations of events due to local seismic sequences (e.g., 1979 in the epicentral area of the 1976 Friuli earthquakes; 1998 and 2004 in the Slovenian area of Bovec; 2004 in the Salò area, Garda Lake), and the increase of events in 2011 and 2012, due both to improvements of the network and to changes in seismicity rates. The completeness magnitude varies in time and space, as described by Gentili *et al*., (2011). Note also that during some years the number of located events coincides with the total number of detected events, and no additional phase readings have been collected: it depends on the technical characteristics of the acquisition systems, working on simultaneous triggering conditions at multiple stations, e.g., during the period 1991-1993. This led to unreliable estimates of completeness for some years, as widely documented by Gentili *et al*. (2011).

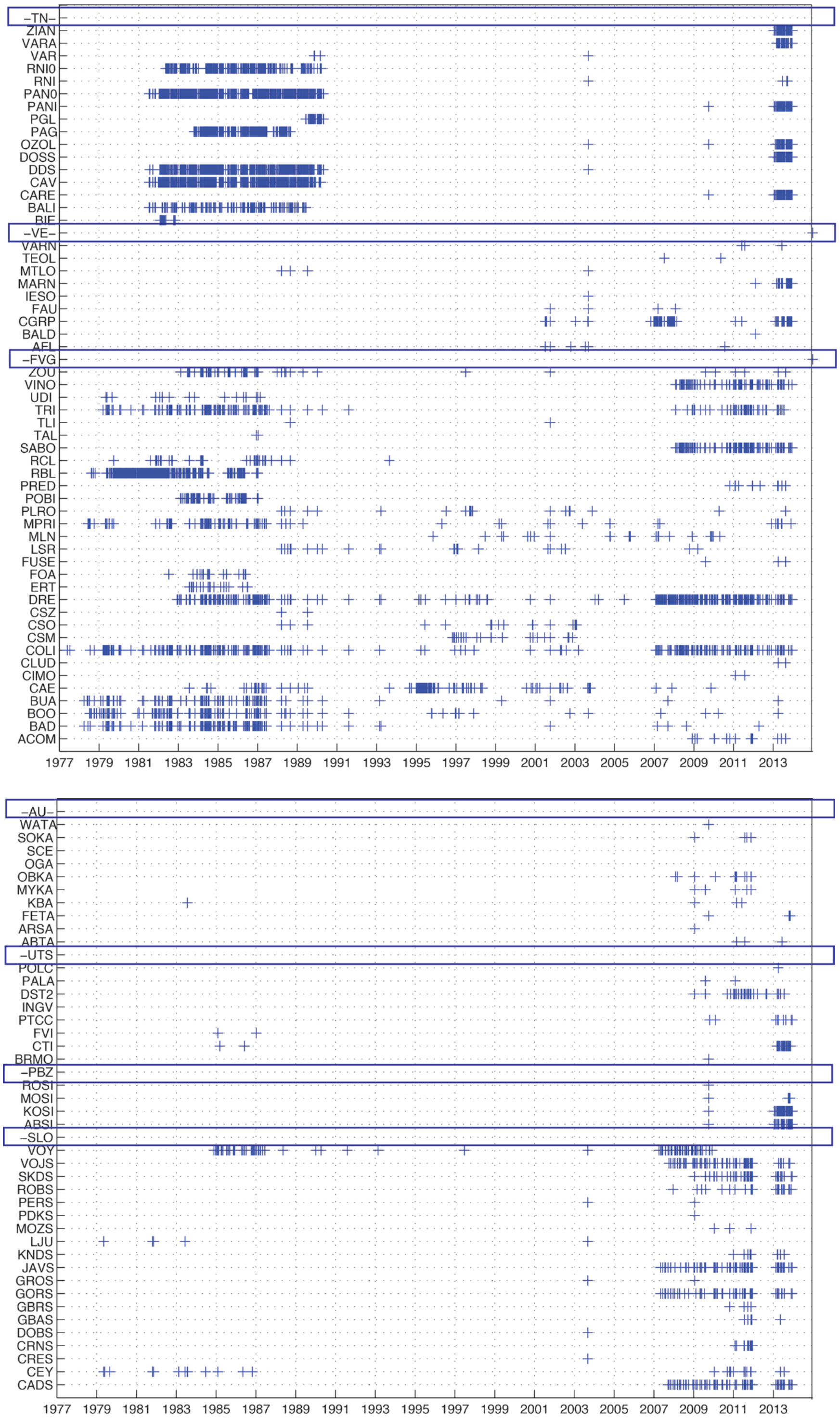


Fig. 5 - Picks of "E" (explosion) and "U" (undefined) events as extracted and integrated from existing bulletins and archives; a) data referred to stations of the regional networks of FVG, TN, and VE, separated by blue rectangles: some relocated stations and labelled with "0" final code; b) data referred to stations of other agencies in the national territory (INGV, the national agency; UTS stands for University of Trieste; PBZ for Bolzano Autonomous Province) and abroad (AU, SLO respectively for the Austrian and Slovenian national seismic networks).

3. Dubious phase selection, integration, and reprocessing

Phases marked by "E" and "U" codes have been extracted from the online published bulletins data, analysed, integrated with other published and unpublished data (e.g., Renner, 1995), and checked, to be homogeneously reprocessed following the standard procedures adopted for the periodic reports to regional administrations [for the year 2012, see Bragato *et al.*, (2013b), Garbin *et al.*, (2013) and Snidarcig and Bragato, (2013)]. The qualification, homogenization and control of phases of explosions and/or dubious events are described hereinafter.

3.1. Explosions and dubious phases in bulletins

Events marked like explosions appear with sporadic readings in the very first bulletin of June-July 1977. More systematic reports are given from April 1978 on, and then they follow the growth of the network that occurred in 1981 (see Fig. 3), when some new stations were installed in the TN area, affected by lower seismicity rates with respect to FVG. Fig. 5 shows the time distributions of the "E" and "U" phases at all the stations, respectively belonging to the regional networks of FVG, TN, and VE (Fig. 5a), and pertaining to other national and international institutions (Fig. 5b).

From the graph, we may note that the identification of explosions decreases abruptly in 1987 in the eastern region (FVG and VE stations); this is probably due to both the increased work duties, for clustering in time of earthquakes inside the area of authority managed by OGS, and the gradual changing in the acquisition/elaboration strategies that led soon to the abandonment of analogue equipment in favour of new digital systems. In the westernmost Trentino area, explosion recognition is documented in the OGS archive until 1990, when the data processing was transferred to the local authorities; phase readings of explosions and undefined events, independently performed by the TN Geologic Survey personnel to compile a local event catalogue (http://www.protezionecivile.tn.it/territorio/Banchedati/Eventisismici/), have not been fully merged into the OGS database. Since 2008, the pickings and hypocentral determinations of events relevant for the TN area have been bounced back again to OGS personnel, but no identification codes of explosions were assigned in 2008-2012.

Note that some detected explosions and undefined events are spread over many stations during the period 1987-2006, thus implying highly energetic events. Some peculiar and recent examples are:

- 2003, September 12 (9:30 UTC) event detected by most of the stations in Italy and abroad: it corresponds to an underwater explosion, notified by maritime authorities; several similar cases, recorded by fewer stations, occurred in the past, too;
- 2009, January 27 (3:30 UTC) event referred as "mining event" in Sostany (Slovenia) by ARSO bulletins;
- a huge collapse landslide in the Dolomites (Mt. Civetta) occurred on 2013, November 16 at 14:22 UTC.

We reckon that some other events of dubious origin are not appropriately marked in the catalogue: for example, this is the case of at least two well-documented events that occurred in the Fadalto area (SW of Belluno, near the S. Croce Lake) on January 12, 2011, (UTC 20:55, M_D 1.1), and January 23, 2011 (16:58, M_D 2.0). They are also known as rumbles ["brontidi",

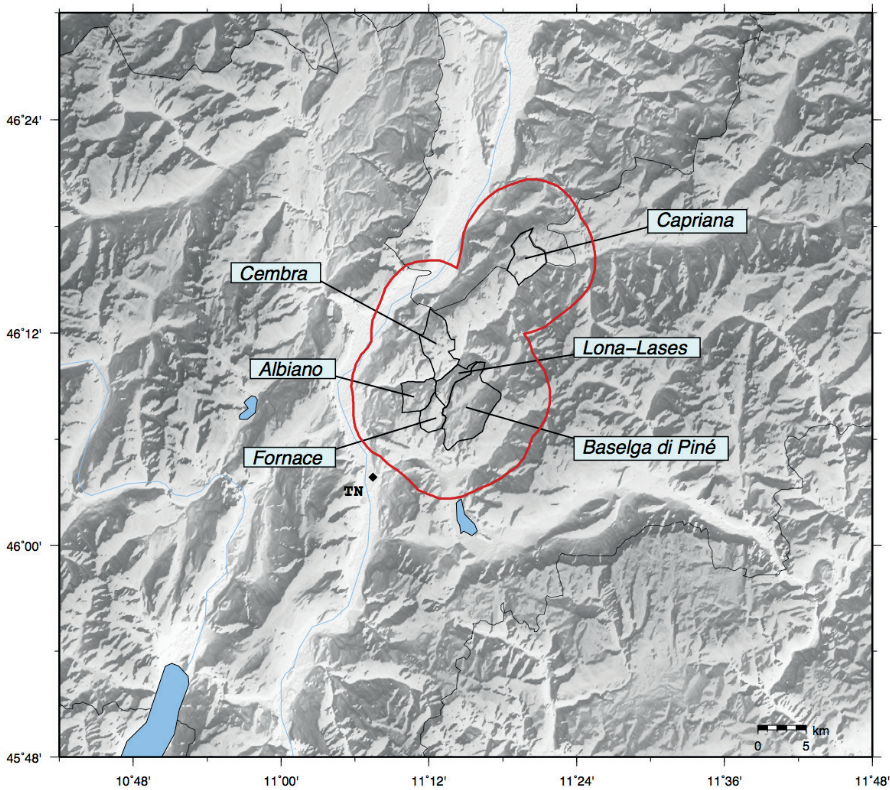


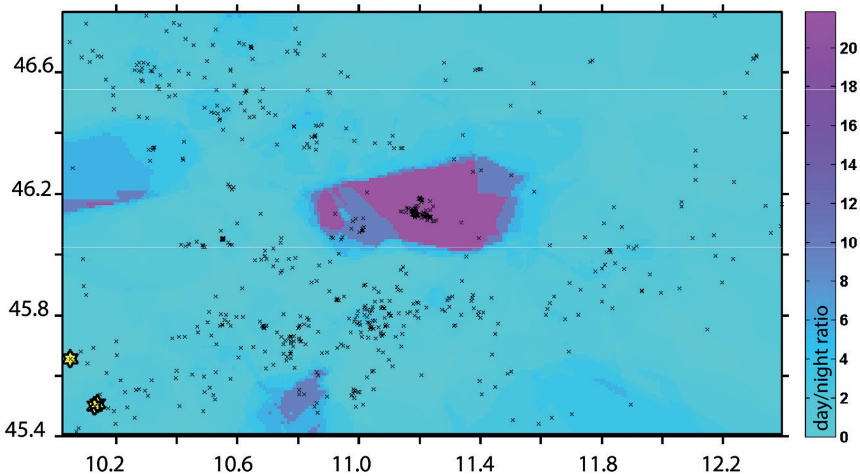
Fig. 6 - Target area for quarry explosions identification, as defined in the 2013 TN data set of located events; the red buffer zone includes quarries that provide alert notification of the explosions.

according to Hills (2011)], as they were felt mainly as acoustic phenomena, and they are probably associated with the groundwater circulation in Karst areas (CRS staff, 2011). Other acoustic phenomena have been reported by local newspapers in the Mt. Baldo (Verona, Italy) area, too, and they are probably associated with frequent small events located in that area; until now they have not been identified nor marked with specific codes in the OGS phase readings database.

Note also that explosions are concentrated at some stations in limited time periods (e.g., CAE in 1995, CGRP in 2007); these are most likely due to local anthropogenic disturbances or to changes in procedure for manual identification and pickings of events. Since 2007, a widespread examination of waveforms has led to a significant increase of explosion readings, mainly for the stations in the Italian Karst area, near the border with Slovenia.

3.2. Data integration with space-time detection of explosions in TN Province for 2013

Fig. 5 very clearly shows that phase pickings for non-tectonic events from TN stations are almost entirely referred to the first period of the network operation, and they are extremely frequent from 1982 to 1991. From 1991 to 2007, the Geological Survey took over the full management of TN stations. As a result, TN data (including event codes) did not enter into the OGS bulletins except for some selected events, already identified and recognised by the FVG and VE stations. Thus, the huge number of explosions documented before 1991 disappears,



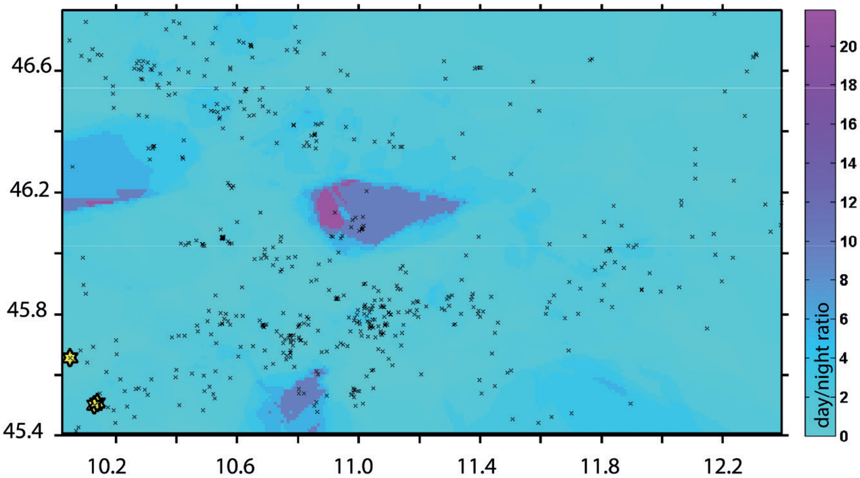


Fig. 7 - Maps of R_q Factor [weighted ratio between the number of events in working and in not-working hours, Zmap by Woessner and Wiemer, (2005)] before (upper frame) and after (lower frame) the identification of explosions and dubious events in TN data set of 2013. A residual anomaly is compatible with quarry activities not reported to the Geological Service.

not for a change in quarries exploitation, but for the lack of metadata sharing. From 2008 on, the data processing was assigned again to OGS; no events tagging for explosions was implemented until 2012. In 2010, a new procedure for identification of earthquakes in the TN area was developed (Garbin and Priolo, 2013); it increases by about three times the number of seismic events recognized in the area, and it lowers the completeness magnitude from ~1.3 to 1.0. Consequently, a huge number of quarry explosions enter in the annual TN reports (e.g., Garbin *et al.*, 2013), making the separation between tectonic and non-tectonic events unavoidable; conversely, not all the events identified in the TN region have been merged in the OGS bulletins, thus diminishing their impact on the seismicity view. A systematic procedure for addressing and labelling the number of non-tectonic events that enter into the catalogues of TN Autonomous Province, was adopted in 2013 (Garbin *et al.*, 2014). During that year, the Geological Survey provided the list of alerts for quarry explosions: it consists of a total of 336 alerts, a huge number, even if not exhaustive of quarry blasts that actually occur in TN

Autonomous Province. The information provided includes the date, hour, and the sector in the quarry where the explosion will take place. Catalogue data matching these alerts in space and time have been ascribed to human activities. Unfortunately time information is not precise, so the automatic procedure implemented to search these explosions in the catalogue must admit a rather large tolerance (2 hours). At an early stage, a 5-km distance buffer polyline surrounding the municipalities where the quarries are located was drawn (Fig. 6). Each event from the TN catalogue is tested to determine if it was included inside the polyline. If the event passes the test, it is compared with alerts; otherwise the event is tagged with a “T” code (tectonic event, not recognized like an explosion). If a time correspondence with an alert is found, the event is tagged with an “E” (event having a corresponding alert), otherwise with a “D” (possible explosion not included in alerts). Finally the “D” events are checked again for compatibility with explosions, evaluating the day of the week, holidays, and working hours. If this last compatibility check is passed, the “D” code is confirmed; otherwise the dubious explosion “D” is reverted back into a tectonic “T” event.

This procedure tagged about 1/4 of the 781 events reported in the TN Autonomous Province catalogue for the year 2013 with an “E” or “D” code, indicating reliable or potential explosions. More precisely, 192 events have been tagged like “E”, 34 with “D”, and the remaining 555 events are considered tectonic earthquakes (and therefore tagged with “T”).

To verify the quality of quarry blast identification in the TN area, the map of R_q parameter obtained with the Zmap software (Woessner and Wiemer, 2005) before and after the events removal is shown in Fig. 7. R_q is a weighted ratio between the number of events in working and in not-working hours. The reduction of R_q “anomaly” is very clear in the central portion of the map. A residual anomaly still exists several kilometres away from the polyline area for which alert information is given: this is most likely due to a spatial cluster of events compatible with other quarry activities whose explosions have not been reported to the Geological Survey.

At the time of the writing of this paper, the TN phase readings have not yet been merged and integrated in the OGS bulletins; notably, the number of explosions and dubious phases identified in only one year with this technique is relevant. For the purpose of this work, we have merged the TN “E”/”D” phases in the “E”/”U” subset identified in §3.1, after a check to avoid duplication of events; we can then treat them jointly, as described later on. Fig. 8 summarizes the distribution of non-tectonic phase pickings on OGS and TN stations, signed with their station code, in two different time frames. Both before and after 1991, the TN stations are the most represented ones; note also that in Fig. 8b, the TN data derive almost exclusively from one-year long data set (2013). The explosions identified in the TN area in 2013 will be used in the future as a learning data set of waveforms, to identify similar events using cross-correlation technique on signals.

3.3. Hypocentral solutions

As previously stated, we want to homogeneously reprocess all the explosions or dubious phases, following the standard procedures adopted by OGS for its bulletins. Most events have one-station readings only, even if sometimes the readings of both P and S phases allow us a rough estimate of the distance with respect to the recording station; if more station picks are available, a locating solution is obtained by HYPO71 code (Lee and Lahr, 1975): with only four phases, no errors estimate is given.

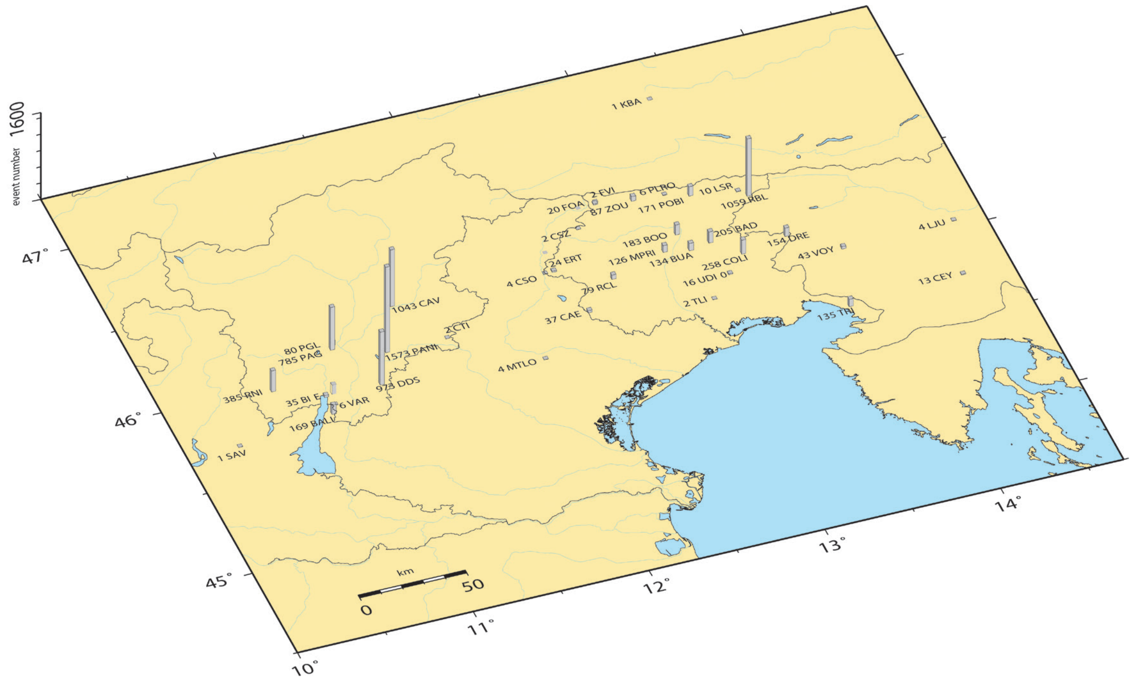


Fig. 8 - Number of phases referring to non-tectonic events detected at each station; a) period 1977-1990; b) period 1991-2013. The data set of explosions and undefined events extracted from bulletins and archives is merged with the specific analysis performed on TN stations for 2013. The column height represents the data sample: note the different scale in the two frames.

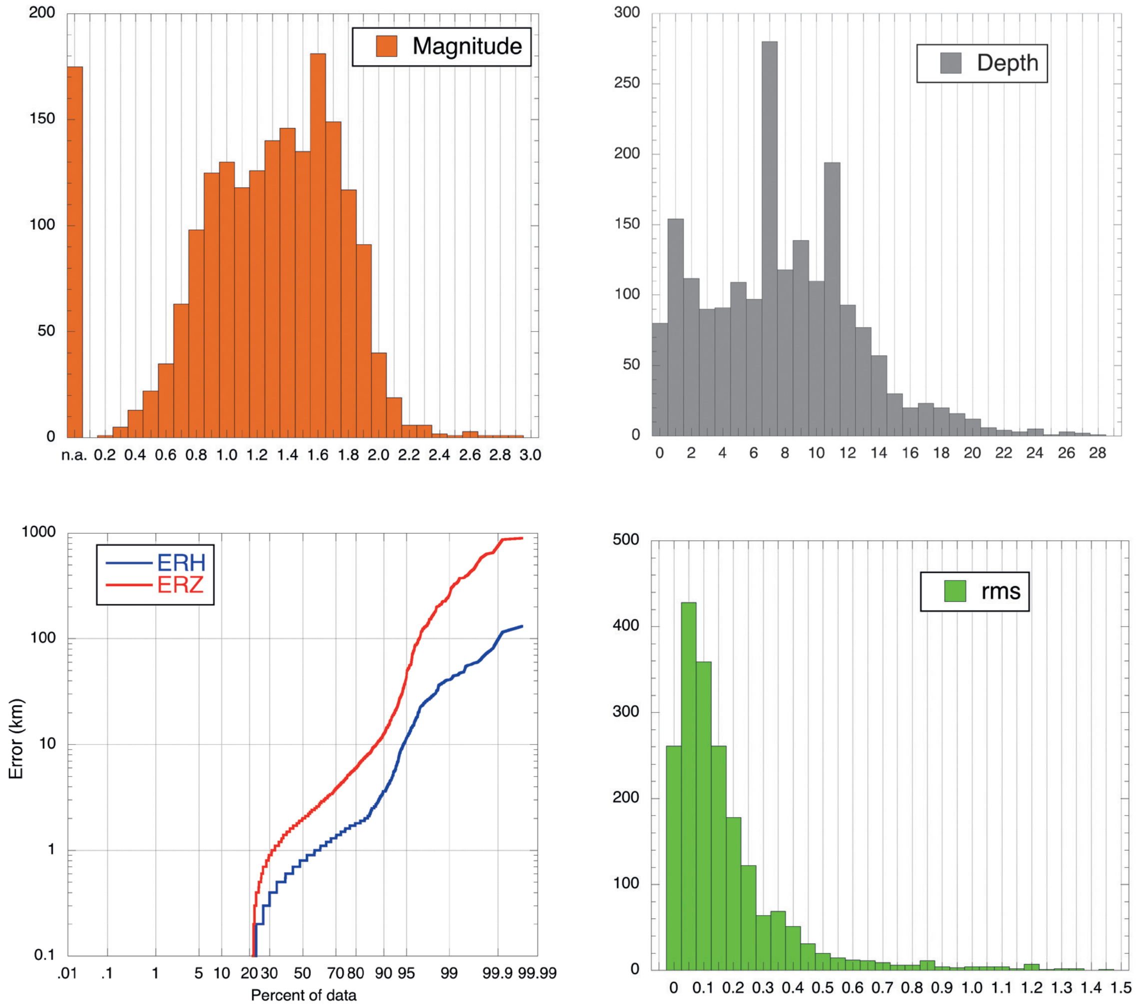


Fig. 9 - Statistical analyses of hypocentral locations obtained with the same procedures adopted for standard processing in OGS bulletins; a) magnitude distribution: data with duration magnitude not assigned (n.a. column, on the left of the graph) come from the TN 2013 data set; b) depth distribution; c) probability plots of horizontal (ERH) and vertical (ERZ) errors; d) histogram of time residuals (rms) of the solutions. The bad resolution of depth is due to station coverage and uncertainties in phase identification.

The same regional velocity model with two layers and half-space, tailored on average velocities/depth markers in the Alpine area (Bressan, 2005), has been used: the *Vp*/*Vs* ratio of 1.78 derives from observations. Magnitude is computed from duration readings when available, using the M_L-M_D relationship calibrated on the OGS stations (Rebez and Renner, 1991); since 2009 for the most energetic events (usually with M_L>3.5) a M_W is given, too, based on full waveform inversion of moment tensor (Saraò and CRS staff, 2014). A reprocessing of early instrumental data of the Trieste station (before 1976 earthquakes) has been very recently published (Sandron *et al.*, 2014), and a new M_W-M_L calibration on an updated Wood-Anderson data set has been tuned (Sandron *et al.*, 2015), but not yet implemented in standard bulletin elaborations. Usually, due to the low energy content, M_L/M_W computation does not apply to the data set of explosions and dubious earthquakes; the use of M_D during the whole lifetime of the network guarantees a certain homogeneity in evaluating the energy contents, even if some systematic bias in duration readings is known (see Gentili *et al.*, 2011).

The data set of "E"/"U"/"D" phase readings has been analysed separately for the periods 1977-1990, and 1991-2013; different features appear and reflect the potentiality and pitfalls of the network. Table 3 summarizes the quality of locations, in terms of the global A-D classes defined in HYPO71, and other commonly used statistical qualifiers. A representation of magnitude and depth distributions, and location errors is given in Fig. 9: events solutions are given as supplementary files too (as an ASCII list of events and in kml format for Google Earth).

Note that regarding 1949 located events:

- 174 have no magnitude estimate (Fig. 9a), most of them come from the 2013 TN data set as duration readings have been gradually abandoned in favour of an automatic computation of amplitude magnitude: 7 events have M_D>2.5, but these estimates, based on signal duration data, have to be taken with great care; nearly all of them correspond to documented explosions in the Trieste Gulf (see the supplementary file);
- the depth (Fig. 9b) is very weakly controlled, mainly due to stations' inter-distance (mean minimum event-station distance is 12.2 km); only 3 events exhibit depths greater than 30 km, but more than 30 events have unacceptable vertical errors (greater than 200 km, see Fig. 9c), thus strongly influencing the mean values of ERZ reported in Table 3;
- about 20% of the located events have no errors estimate (set to zero, in the probability plot of Fig. 9c); about 70% of them have acceptable horizontal errors (smaller than 3.5 km, corresponding to the 90% probability on the blue curve in Fig. 9c). Errors in terms of time residuals (rms, in Fig. 9d) do not show anomalous patterns with respect to the residuals of the data set of tectonic events.

Note also that more than 2,500 events in the actual data set have no location at all, thus remaining assigned to the nearest station. These numbers will be subjected to a rapid and relevant increase as far as "fake" earthquake oriented reprocessing is performed [e.g., for the TN 2009-2012 data set, or for peculiar case like in the Fadalto area: CRS staff (2011)].

Table 3 - Synthesis of event and location quality for the data set of explosions and dubious events gathered in this study. Numbers in brackets, in the second row, refer to the TN data set for 2013 described in §3.2.

Period	Total events	Total located events	HYPO71 Quality	With Mag	Num Ph	Gap	RMS	Total with ERR	Mean ERH	Mean ERZ
1977-1990	3399	1505	A=0 B=267 C=941 D=297	1502	6.73	195	0.17	1203 79%	3.66	17.63
1991-2013 (TN2013)	1097	444 (226)	A=0 B=77(49) C=277(166) D=90(11)	273	7.64	159	0.18	331 75%	1.84	11.52

3.4. Analysis of results

The maps in Fig. 10 give a comprehensive view of spatial and time distribution of non-tectonic events. In Fig. 10a, symbol colour indicates the depth, blue circles and vertical lines

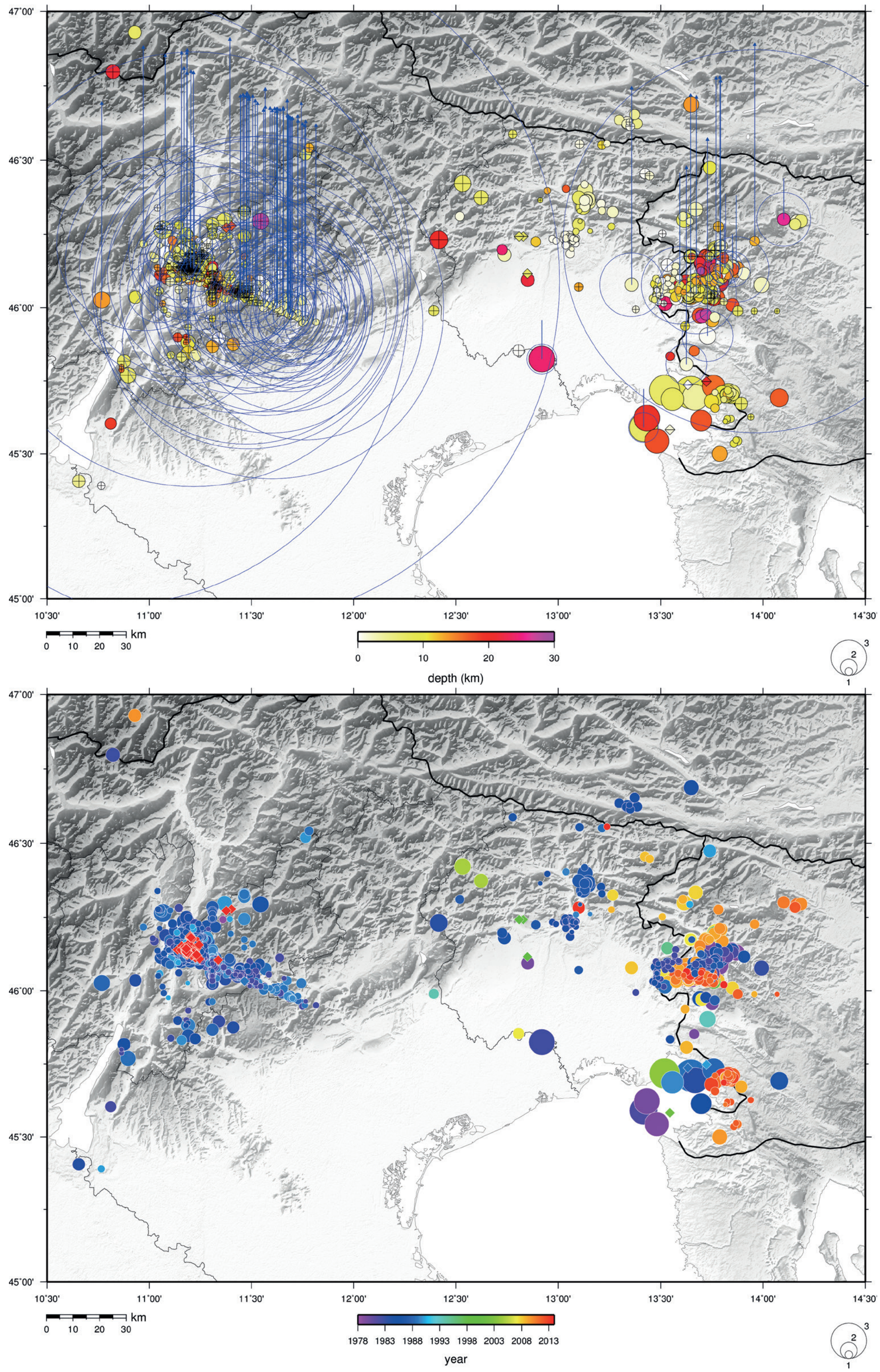


Fig. 10 - Maps of non-tectonic events located in this study: a) comprehensive representation of magnitude (symbol size), depth (colour), and errors (blue circles and bars) assigned by the hypocentral locations; b) space-time distribution of events according to the colour scale.

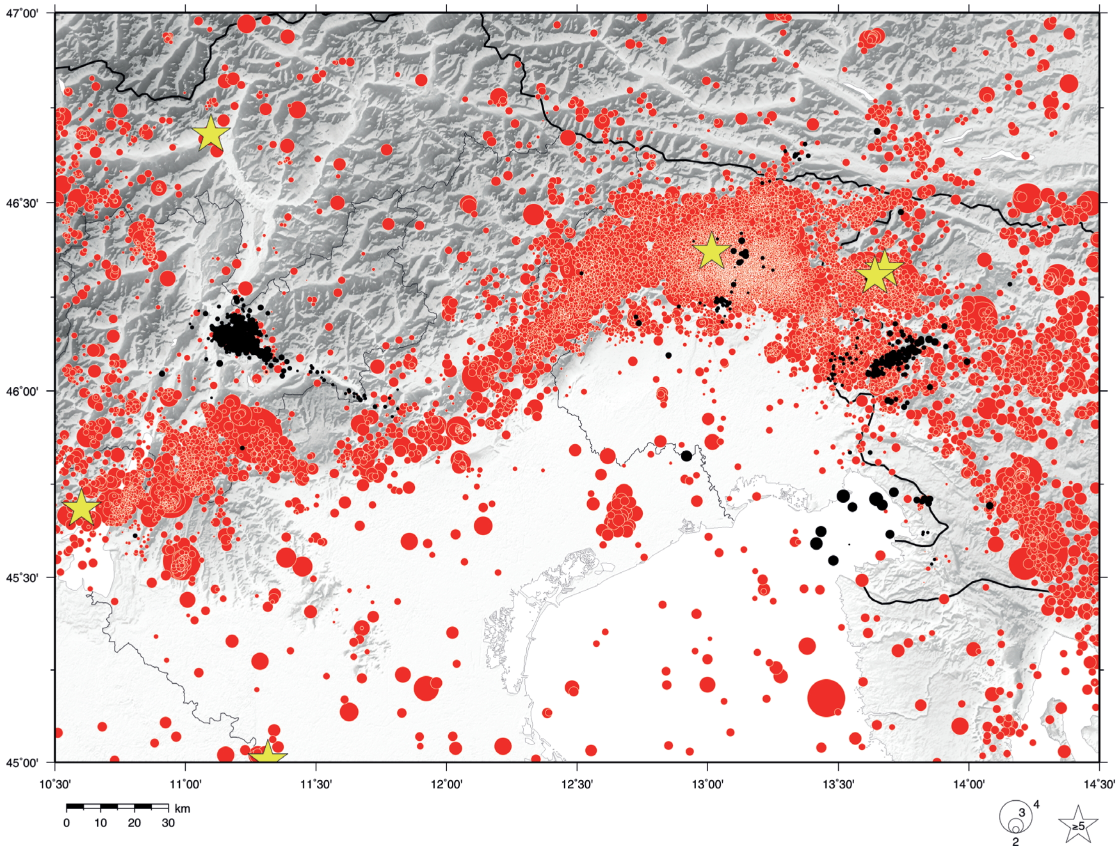


Fig. 11 - Map of tectonic (red circles, yellow stars see the legend of magnitude) versus non-tectonic events (in black) detected by OGS in the period 1977-2013. About 60% of the events identified and isolated as explosions or dubious events by this work are reported in the catalogue, but only the extended printout of bulletins permits their identification as non-tectonic events. The implementation of an extra field for non-tectonic events in online queries via http://rts.crs.inogs.it/en/search/advancedsearch.html is ongoing.

represent the horizontal and vertical errors in scale, and they are plotted only if greater than 4 and 13 km (90% probability in Fig. 9c) respectively. Events without magnitude are represented by little rhombs. In Fig. 10b a different colour scaling represents the date of the events.

The group of events located around the Trieste Gulf exhibits the highest magnitude values: as previously cited these events are underwater explosions, reported in the late 1970s, in the 1980s, and also recently in 2003 by the Maritime Authority; thanks to the integration of Slovenian stations in the real-time detection of events, some quarry blasts are documented too [mostly in nearby Sezana (Slovenia)]; the statistical locations errors are usually low, but the depths are not reliable, probably due to imprecise S-phase identification and very poor azimuthal coverage.

A huge group of events is located east of S. Pietro al Natisone (Udine, Italy) and south of Tolmin (Slovenia); they are documented during nearly all of the lifetime of the OGS network (Fig. 10b), but locations are scattered along different alignments with time, following the changes of station geometries. Note the better depth control of data located inside the Italian territory.

Toward the NW, some events are located in the upper Tagliamento River area, and nearby Hermagor (Austria); most of these events date back to the 1980s, when analogue continuous recordings were available but in off-line mode (e.g., RBL station).

Very few events are located near the border of the FVG and VE regions, despite the fact that some stations (e.g., CAE, CGRP; see Fig. 5a) have plenty of single station readings. In the plain, the main event is in the Portogruaro area in 1982, and it has unrealistic depth and one of the highest magnitudes (M_D=2.6): due to its location and magnitude, the event has been carefully checked in the original recordings. No authorities's notification of an explosion has been recovered, but the waveforms are coherent with a quite energetic surface explosion and they are extremely similar to the ones of other reported explosions at sea (e.g., ID n. 19, November 24, 1981), with amplification and persistency of seismic waves in the soft, thick alluvial deposits of the plain.

But the biggest group of events (event ID n. 117, July 31 at 9:50) is located in the TN area, and it appears as a cloud of events in the Porphyry Quarry District, NE of Trento, with a peculiar NW-SE elongated whisker that follows the Valsugana Valley. Location errors are huge, or undefined (black vertical and horizontal lines inside the event symbols) because of insufficient phase readings. We reckon that most of the events of the alignment occurred in 1988-1989; they have usually been located with two to four TN local stations (CAV, DDS, PANI, RNI), and they show huge residuals that can be explained only by changes of stations' location not reported in the stations book, or by problems in the local time recordings (misalignment of clocks); bias in phase readings could also have occurred. Most of these solutions are not given in the bulletins, as they were filtered out by errors thresholds in locating solutions; nevertheless, these problems could affect similarily the location of tectonic events, and some alignments can therefore be artifacts, causing misleading interpretation of the seismic signature of existing faults.

We finally performed a check to estimate how many events among the 1949 non-tectonic events relocated in the present work are still reported in the online bulletins without a specific tag in the solutions that allows the identification of explosions or dubious events. About 60% of these relocated events have been identified (Fig. 11) and are going to be tagged in the database that supports interactive queries on bulletins.

4. Conclusions and perspectives

The benefit of identifying and tagging explosions and dubious events in an earthquake catalogue is a better representation of natural seismicity. This aspect is particularly felt these days, given the growing interest the theme of anthropogenic or induced seismicity (e.g., https://sites.google.com/site/s2stohaz/issues/sismicita-indotta). The extraordinary maintenance of phase pickings on the database managed by OGS for north-eastern Italy that we have done in this study has led to the extraction of more than 4,400 events, already identified in the original data as non-tectonic events. By using the same standard procedure adopted for the compilation of bulletins, about 40% of them may be located, and the magnitude computed from duration data. They are unequally distributed in space and time (Fig. 10); their identification follows the changes in network geometry and strategies for data treatment and dissemination, but most of these data are referred to the first period of the OGS network (1977-1990), for which no digital waveforms are available.

Before we started this analysis, about 60% of the non-tectonic events we relocated in this study were reported in the bulletins available on the OGS website (http://www.crs.inogs.it/bollettino/RSFVG/), without an identification code that simply warned the users on the nature of such events; the other 40% or so have been already discarded from the catalogue for the bad quality of their locations. We therefore decided to tag them in the database supporting interactive queries (http://rts.crs.inogs.it/en/search/advancedsearch.html) to avoid misinterpretation of the seismicity patterns. We are also modifying the masks of online bulletins, and implementing new functionalities for combined representations of tectonic, explosive, and other dubious or undefined events. In the TN area, the region where these events are very common due to extensive quarry activity, a special analysis has been performed to reckon events on the basis of space/time coincidence with explosion notifications. These events should now be used as a learning set for explosion identification based on waveform cross-correlations.

The catalogue of non-tectonic events in north-eastern Italy will be maintained and implemented in the near future with a full reprocessing of data using location techniques not yet adopted for ordinary bulletins.

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