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Misunderstood "forecasts": two case histories from former Yugoslavia and Italy

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ABSTRACT Although earthquake prediction remains an ultimate goal of seismology, up to now only a very few events have actually been forecasted, while for many of them wrong or doubtful predictions were given and even some misunderstandings were produced. After reporting a couple of examples on the subject, the paper focuses on an accurate revision of the seismological data of the 1976 seismic sequence in Friuli (north-eastern Italy), as well as on the analysis of the space distribution of the earthquakes aiming at investigating if any clue of possible identification of the epicentre of the main aftershocks was possible at that time or should be possible today. The final consideration is that, even with a good (or good enough) seismic monitoring, there was no clear evidence of epicentre migration towards the future location of the major events.

Key words: earthquake forecasting, foreshocks, 1969 Banja Luka earthquake, 1976 Friuli earthquake.

1. Introduction

It is often difficult to transmit properly the information about the evolution of a seismic sequence from scientists to the population and unintended consequences can sometimes occur. The reason is that the earthquake process remains, to a large degree, unexplained by science, while the communication media ask for certainness, possibly provided by sensational news. Thus, information based more on common sense than on poor statistics of past events are often sweetened in a "journalistic" fashion and remote possibilities are presented as certainties. Two examples are given of how the mere communication to the relevant authorities of the existence of a situation which is possibly critical, even if constantly evolving, with an outcome which is uncertain but subject to analysis, has had completely different consequences for the scientists who disseminated the declaration. The first example refers to the 1969 Banja Luka earthquake, in former Yugoslavia, which was followed by a stronger aftershock the day after. The second concerns the 1976 Friuli earthquake, in north-eastern Italy. In this case, the main shock was preceded a minute earlier by a smaller foreshock and also four strong events occurred four months later in the same epicentral area and an additional one 16 months after the mainshock.

This work mainly focuses on this second case because an accurate full revision of the seismological data and an analysis of the space distribution of the earthquakes have been performed. Its aim is to investigate if, with better data (the revised locations presented here), unavailable at the time of the earthquake, it would have been possible to forecast the occurrence and the location of the strongest aftershocks characterizing the seismic sequence.

2. Two case histories

Some interesting and common aspects relating the communication chain from the scientist to the population, filtered by the authorities in charge, are described. A further peculiar aspect to underline is that the two earthquakes occurred in different countries, respectively, in the former Yugoslavia and Italy, but the approach to the phenomenon is very similar.

2.1. The 1969 Banja Luka earthquake

The city of Banja Luka (at that time in Yugoslavia, today in Bosnia and Herzegovina) was heavily damaged by two powerful earthquakes in October 1969 (Fig. 1). The first one was on Sunday 26 October at 4:36 p.m. (local time); its local magnitude (M_L) was 6.1 and the maximum intensity VII-VIII (Grünthal *et al.*, 2013) in the Mercalli - Cancani - Sieberg (MCS) scale. The earthquake caused a lot of damage to the town of Banja Luka and its surroundings, and more than 20 people died under the collapsed buildings.

The strongest earthquakes in the sequence are listed in Table 1 (after Trkulja, 2009) and depicted in Fig. 2. Intensity estimates are in MCS scale, and the magnitudes are macroseismic (Trkulja, 2009).

Fig. 1 - Damage in Banja Luka caused by the 1969 earthquake.

Urban legend has it that in the morning of the following day there was a successful prediction of a forthcoming and even stronger earthquake, which saved many lives.

If we try to follow the situation with the help of the contemporary press, this is what happened: after the first shock, in the afternoon of 26 October, there were several aftershocks.

Table 1 - Seismic activity of Banja Luka area during the 1969 - 1970 sequence. The data are taken from the study of Banja Luka earthquakes by Drago Trkulja, former head of Banja Luka Seismological Observatory (Trkulja, 2009).

Date	Time (GMT)	Epicentre φ° N	Epicentre λ° E	Depth (km)	I_0 MCS	M_L
1969 10 26	15 36 43.8	44.90	17.25	15	VII - VIII	5.6
1969 10 27	02 55 30.7	44.95	17.00	10	VI - VII	4.8
1969 10 27	08 10 56.2	44.85	17.20	25	VIII - IX	5.6
1969 10 27	08 53 38.7	44.94	17.05	15	VI	4.7
1969 10 27	11 07 55.5	44.92	16.92	17	V	3.9
1969 11 03	16 45 46.1	44.78	17.25	12	IV	3.0
1969 11 04	03 24 44.9	44.75	17.33	10	V	3.0
1969 11 18	03 32 51.2	44.73	17.30	10	V	3.0
1969 12 31	13 18 30.1	44.88	17.22	18	VI - VII	5.3
1970 01 02	19 45 19.0	44.87	17.47	20	IV - V	4.1
1970 04 06	21 54 09.3	44.88	17.43	15	V	3.6
1970 04 06	21 56 14.2	44.90	17.33	10	IV	2.6
1970 04 07	03 17 10.5	44.70	17.33	7	IV	2.6
1970 04 25	11 07 28.6	44.75	17.25	8	VI	3.5
1970 10 20	13 45 56.9	44.80	17.20	15	V - VI	4.5
1970 10 20	20 19 23.9	44.80	17.30	8	VI - VII	4.6

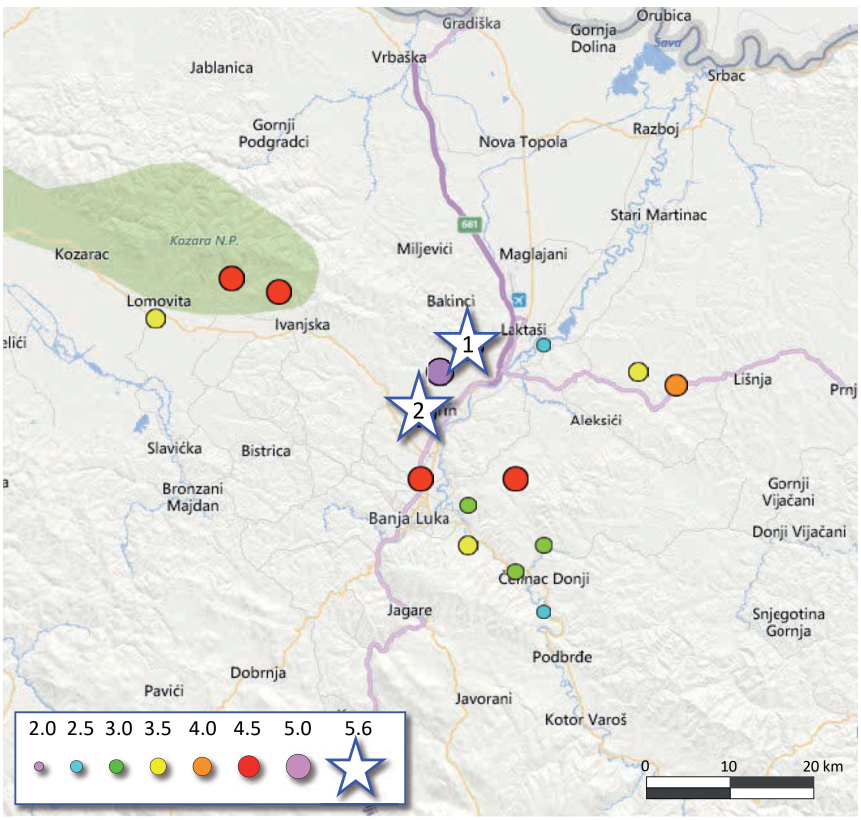


Fig. 2 - Epicentres of the Banja Luka seismic sequence (data from Trkulja, 2009). The two stars show the main events of 26 (no. 1) and 27 (no. 2) October.

The seismologists of the time were analysing the records of their stations, changing the paper in their analogue instruments every few hours, in order to be able to have updated data. The records of the seismographs in Ljubljana were analysed by professor Vladimir Ribarič, who at the time was the head of the Astronomical - Geophysical Observatory. Worried about the number and the magnitudes of the aftershocks, early in the morning on Monday 27 October he spoke on the phone with Mr. Gunić, vice-president of the Banja Luka Assembly. Ribarič warned Gunić that it was possible that more earthquakes would follow, as the grounds needed to stabilize. Therefore, people should be careful and not stay inside the damaged buildings, which could have been shaken again.

Only some hours after that conversation, on 9:10 a.m. (local time) on Monday 27 October, there was another powerful earthquake, stronger than the first one. Its M_L was 6.4 and its maximum intensity is estimated to be VIII-IX MCS (Grünthal *et al.*, 2013).

The media seized on the news of the conversation and spread it. In their interpretation, Ribarič had made a forecast. His name was across the front pages of the Yugoslav newspapers (Fig. 3) and he became a kind of hero.

However, from the very first day, Ribarič was keen to correct the mistake and kept explaining, in the media interviews that followed, that he was only speaking about commonly known things, as aftershocks are to be expected after a strong earthquake and some of them might have considerable size.

In the interview published by the Slovenian newspaper Delo on 31 October 1969 (Fig. 3a), he said: "I was at home, when I was told that a strong earthquake had happened somewhere close. I immediately went to Golovec (the location of the seismological observatory). At 6 a.m. next day, I was called from Banja Luka. They wanted to know about the "habits" of earthquakes, was there anything to be afraid of etc. They didn't call me because I were some super-seismologist and the rest of my colleagues were not important, but simply because they first called Sarajevo and then Zagreb, and no one was there to pick up the phone. It was too early and they found me (at the observatory) by chance. I told them (there was vice-president of the Banja Luka Assembly on the other side of the line) that weaker earthquakes usually follow a strong one, until everything calms down. As all the buildings are shaken and cracked, you do not need a strong earthquake for bricks to start falling down or for a collapse to happen. I, therefore, advised them to be careful. I heard that they had really warned people not to stay inside the buildings, so on Monday morning (in the time of the second catastrophic event) the majority of the inhabitants were in the streets and parks."

Later, Ribarič laughed, when he read that he had "predicted" the catastrophe. "Unfortunately, I have no such abilities", he said, "although I wouldn't mind having them".

The epilogue of the proclamation of Ribarič's "prophetic abilities" was not particularly pleasant for him. When he came to Banja Luka on Wednesday 2 October 1969, he noticed that Mr. Gunić was looked rather cross. Fortunately, they solved the problem quickly. Mr. Gunić had read in the newspapers that Ribarič "predicted the catastrophe", although he remembered very well that they were mentioning only caution, as "you never know". "Why didn't he tell me about the catastrophe, if he really knew it was going to happen?"

In the archives of the Slovenian Environment Agency, there are letters and postcards, sent by citizens from all over Yugoslavia after the Banja Luka earthquake, thanking Ribarič for saving so many lives and congratulating him for his heroism.

a

Golovec je opozoril

Inž. Vlado Ribarič je v telefonskem razgovoru opozoril podpredsednika banjaluške skupščine, da utegne priti do novih potresnih sunkov

LJUBLJANA, 27. okt. Dobre tri ure pred silovitim potresnim sunkom, ki je ob 9.11 zamajal vso Banjaluko, je vodja astronomsko-geofizikalnega observatorija na Golovcu, inž. V. Ribarič v telefonskem razgovoru takole opozoril podpredsednika mestne skupščine Banjaluka Gunića: »Danes utegne priti do naknadnih potresnih sunkov. Dobro bı bilo, da se ljudje ne bi zadrževali v poslopjih, šolah in javnih objektih.«

Epicenter enega izmed 15 potresnih sunkov, ki so včeraj in danes majali mesto ob Vrbasu, je bilo natanko na področju Banjaluke in potresni valovi so se s silovito razdiralno močjo širili na vse strani. Ta potres je presegel osmo stopnjo po mednarodni Mercalli - Cancani-Siebergovi lestvici, ki ima skupno dvanajst potresnih stopenj. Hipocenter je bil pod zemljo v globini med 11 in 18 kilometri. potresna magnituda pa je po Richterjevi lestvici znašala od 5.3 do 5.5. Minilo je samo pol ure in seizmološki instrumenti na Golovcu so ob 9:44 in 9.54 zaznamovali še dva šibkejša potresna sunka, ki sodita v takoimenovane naknadne potrese.

Četrti potres v Banjaluki

V zadnjih 81 letih je doživela Banjaluka že več močnih potresov: 30. marca leta 1888 je meščane preplašil močan potres sedme stopnje, potem je bilo zatišje, ki je trajalo več desetletij, ko je 10. oktobra leta 1935 ob 13.07 mesto ob Vrbasu spet doživelo precej močan potresni sunek šeste stopnje. Zanimivo je. posebno v primerjavi z letošnjimi dogodki, da je že naslednji dan, 11. oktobra leta 1935 elektronske aparature na Golovcu večkrat odpovedale, zato so se strokovnjaki v Ljubljani, Zagrebu in Beogradu posvetovali, ko so določali epicenter obeh silovitih sunkov. Tako so šli v izgubo dragoceni podatki, ki naj bi jih zaznamovale najbolj učinkovite seizmološke aparature na Golovcu. Elektromagnetne naprave niso pisale podatkov, ko je šlo za najmočnejše sunke, medtem ko poznejši valovi niso tako zanimivi. Elektronski ojačevalec za vidljiv zapis ni mogel slediti potresnim dogodkom. Vse to kaže. da bi morali imeti v Ljubljani poleg najbolj občutljivih naprav še manj občutljive merilce potresov. Zato je običajno, da imajo seizmografski zavodi na Švedskem in v Nemčiji boljše potresne podatke o našem območju, čeprav so zelo oddaljeni.

● **Ali sodite po vaših izkušnjah, da bo prišlo v Banjaluki in njegovi okolici do novih potresnih sunkov? Kakšne so možnosti za preselitev potresnega epicentra v Ljubljano?**

Ribarič: »Vsekakor bodo še naknadni potresi, vendar mislim, da je najhujše že mimo, saj je že zdaj nenormalno, da sta si v Banjaluki sledila dva tako huda potresa. Malo je verjetno, da bi se potresni v Grčiji ali Albaniji, vendar je Jugoslavija med evropskimi državami eno najmočnejših potresnih območij. Po potresnem zemljevidu prof. Jelenka Mihajlovića sta Ljubljana in Maribor v deveti potresni stopnji, vendar je Vladimir Ribarič izrazil svojo znanstveno domnevo, da bi mesto ob Dravi pravzaprav spadalo v osmo potresno stopnjo. Naši strokovnjakı so medtem že začeli z izdelavo

VLADO RIBARIČ

mikro-rajonizacije in opravili celo vrsto geofizikalnih in geoloških meritev, da bi izdvojili cone, ki so manj sprejemljive za močne potrese.

● **Katera so tista območja v Ljubljani, ki so najbolj občutljiva za potresne sunke?**

● **Ali lahko pride pri mikro-rajonizaciji potresnih območij tudi do takšnih pomot, ki bi lahko imele katastrofalne posledice?**

Ribarič: »Metodika naših raziskav je zelo celovita: vzamemo celo vrsto metod in takrat, ko pretežno število znanstvenih raziskav dokaže, da lahko na tem in tem območju gradimo poslopja, ki bi vzdržala recimo osmo stopnjo, takrat je minimalna verjetnost, da bi prišlo do katastrofe, ki je pravzaprav možna samo, če graditelji ne bi upoštevali gradbenih normativov. Res pa je, da se statiki-projektanti v glavnem držijo naših norm.«

Nenehni telefonski pozivi

Nenehni telefonski pozivi so nas prekinjali, medtem ko smo se z Vladimirjem Ribaričem pogovarjali v njegovi pisarni na Golovcu, saj je med Ljubljano, Zagrebom, Beogradom, Sarajevom in Banjaluko danes zares »vroča telefonska linija«, kajti zaradi preslabe opremljenosti seizmoloških postaj so izmenjave podatkov običajne v vsakovnemu delu. Res je sicer, da obstaja zvezni projekt za modernizacijo seizmoloških postaj in izdelavo zemljevida maksimalnih intenzitet, ki ima balkanski karakter in ga materijalno podpira tudi UNESCO, toda poraja se že štiri leta in še do danes niso zagotovljena zvezna in republiška sredstva za njegovo

Fig. 3 - Facsimiles of newspaper articles reporting on Ribarič's "prediction": a) Delo, Ljubljana daily, 28 October 1969, year XI, no. 296, page 2; b) Politika, Belgrade daily, 30 October 1969, year LXVI, no. 20142, page 4.

b

ПРЕД САМУ ТРАГЕДИЈУ У БАЊАЛУЦИ

РИБАРИЧ ЈЕ УПОЗОРИО

На основу изучавања сеизмологије, Рибарич је претпостављао могућност новог и јачег потреса

Љубљана, 29. октобра

Дописник „Политике" из Новог Сада јавио је да ће инж. Владо Рибарич бити гост новосадског скупа и да се разговарало о посебном признању овом савесном научнику који је, пред саму трагедију, упозорио Бањалуку на могућу опасност.

Звучи невероватно, али је ипак тачно: инжењер Владо Рибарич, вођа астрономско-геофизичке опсерваторије на брду Головец изнад Љубљане, упозорио је трагичног јутра у 6 часова потпредседника Скупштине Бањалука Гунића на евентуалну могућност нових јаких, разорних потреса.

— Тачно је да сам у телефонском разговору упозорио потпредседника Бањалуке на овакву могућност — рекао нам је инжењер Владо Рибарич — али то није била никаква прогноза земљотреса, како се то погрешно представља.

— На основу чега сте онда дошли до оваквог закључка?

— Анализирајући у недељу наноћ сеизмолошке податке о првом земљотресу, пало ми је пре свега у очи да су уобичајени накнадни потреси после главног удара, такозвани „афтершокови" на бањалучком подручју неуобичајено учестани и јаки. Познајући приближно механизам земљотреса дошао сам до закључка да се земља неће умирити, да ће доћи до нових потреса, при чему није искључена могућност нових јаких удара. То сам ујутро саопштио потпредседнику Бањалуке упозоривши га да и код потреса мање јачине може да дође до рушења објеката који су већ били начети у недељном земљотресу. Сматрао сам, наиме, да Бањалучани немају довољно искуства са земљотресима и због тога сам посебно препоручио Гунићу да грађани не улазе у куће и да одмах не уклањају рушевине. Разуме се, додао је Владо Рибарич, да нисам могао да предвидим да ће тај земљотрес да буде тако разоран, прилбижно исте јачине као онај катастрофални 1963. године у Скопљу. На такав закључак упућују и последњи подаци о томе да су неки потоци изменили ток, да се појавио гас и слично. Срећа у несрећи је у Бањалуци била, међутим, у томе што се хипоцентар налазио на 11—18 километара, док је у Скопљу био знатно ближи, на свега 3—5 километара испод површине земље. Али због дубоког хипоцентра испод Бањалуке погођено је и оштећено знатно шире подручје него што је то био случај у Скопљу.

— Шта мислите, да ли је најгоре код Бањалуке прошло?

— Готово је сигурно да ће бити још накнадних потреса, али мислим да је најгоре ипак прошло. Ненормално је већ то што су у Бањалуци уследила два учестала јака потреса. Ситуација се смирује. потреси су све слабији, а опада и њихова учесталост. Немам основе да верујем да ће се земљотресни епицентар преселити сада из Бањалуке на пример у Љубљану, Макарску или у долину Неретве, иако постоје теорије о миграцији епицентара. Разумљиво да допуштам могућност да се земљотресни центар пренесе негде ближе Бањалуци, рецимо у околину Славонског Брода.

☆

После боравка у Београду — 1954. године — 26-годишњи Владо Рибарич долази на љубљански Природно-математички факултет, где најпре постаје асистент, а затим виши стручни сарадник Љубљанског универзитета и вршилац дужности директора Геофизичке опсерваторије у главном граду Словеније.

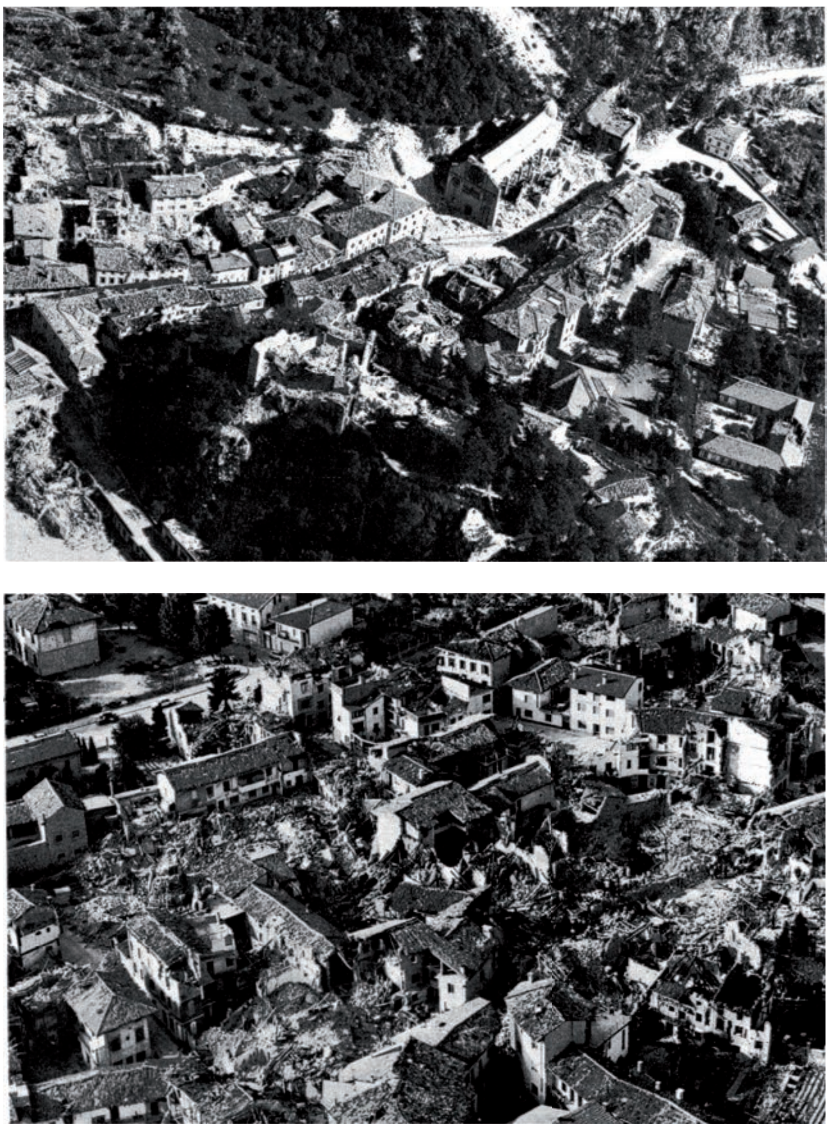
Владо Рибарич, такође, тесно сарађује са љубљанским Заводом за испитивање материјала на микрорејонизацији сезмичких подручја у циљу израде нове сеизмолошке карте овог дела Југославије. Нарочито је запажена Рибаричева студија сеизмичности подручја СР Словеније, рађена за „Кидричев фонд" у којој се обрађују сеизмичка збивања у Словенији још пре десетог века.

Године 1964. „Цанкарјева заложба" у Љубљани издаје у оквиру едиције „Планете" Рибаричеву књигу посвећену трагедији у Скопљу. Под насловом „Земља се тресла" аутор на веома популаран и за омладину доступан начин објашњава појаве које доводе до земљотреса и катастрофа. Књига је доживела велики успех.

Душан Димитријевић

2.2. The 1976 Friuli earthquake

The second example refers to the Friuli earthquake of 1976, the first seismic event in Italy to involve both the international scientific community and the state structures, and that would subsequently gave rise to the Civil Protection Service. In fact, the 1968 Belice earthquake in western Sicily did not stimulate a huge scientific research (see e.g. Haas and Ayre, 1969; Monaco *et al.*, 1996), especially as regards the seismological aspect; conversely to what the Friuli earthquake did (see Slejko, 2018). On 6 May 1976 at 9:00 p.m. (local time) an earthquake of M_L 6.4 struck central Friuli (Fig. 4) causing nearly 1,000 deaths [for a complete review of the event, see Carulli and Slejko (2005) and Slejko (2018)]. The earthquake was preceded a minute earlier by a quake of M_L 4.5 that allowed at least some people to find shelter before the devastating tremor. No shocks in the affected area were recorded in the days before 6 May as the existing instrumentation in the seismological stations of Trieste and Ljubljana, located, respectively, at 70 and 100 km from the epicentral area, did not enable the seismologists to detect low magnitude events in central Friuli. Various Italian and international scientific institutions (Istituto Nazionale di Geofisica, Comitato Nazionale per l'Energia Nucleare, Catania University, Vienna University, Munchen University) deployed temporary stations in Friuli and Carinthia soon after the main shock of May. In particular, a temporary seismic network, set up by the Institut de Physique du



a

b

Fig. 4 - Damage caused by the Friuli earthquake (Briseghella *et al.*, 1976): a) Gemona; b) Osoppo.

Globe of Strasbourg (IPG), operated in the epicentral area since late May 1976, in order to monitor the evolution of the earthquake sequence. The number of shocks and their magnitudes gradually diminished in time and in August 1976 it seemed that the seismic sequence was over (Finetti *et al.*, 1979). In early September, however, there was an upsurge in the number of earthquakes recorded by the Trieste station, with four strong events on 11 September (M_L 5.4 and 5.6) and 15 September 1976 (M_L 5.9 and 6.1). These shocks caused more victims and damage in the same epicentral area of the May earthquake (Carulli and Slejko, 2005).

On 26 September 1976, a further increase in the local seismicity was noted on the recordings of the IPG temporary network. Based on the previous experience (the increase of seismicity in early September which preceded the cited strong aftershocks of 11 and 15 September), professor Icilio Finetti, director of the Experimental Geophysical Observatory (OGS), the institution managing the seismological station of Trieste, issued a press release. The newspaper Il Messaggero Veneto reported on 27 September 1976: “Today the seismic activity shows a notable increment with respect to the previous days; as already mentioned, it is difficult to understand the correct meaning in terms of short term forecast. This increment of activity could perhaps predict a more powerful earthquake, without anyway reaching the destructive level of the previous events, but could also have no specific meaning”. The OGS press release was reported by all the media and was met with great apprehension among the population of Friuli but, fortunately, no strong earthquake occurred.

As reported by the newspaper Il Gazzettino of 28 September 1976, Mr. Giuseppe Zamberletti, then special commissioner for the Friuli earthquake, sent a telegram to Finetti stating: “The news spread by OGS about forecasts on the evolution of the seismic sequence have caused alarm and panic among the population and called people employed in the reconstruction away from the workplace. In order to avoid similar situations in the future, which greatly aggravated the circumstances in the areas already affected by the earthquake, I invite you, then, to ensure that any news about the seismic sequence should be provided to the media by the press office of the government commissioner in the prefecture of Udine, with the approval of the commissioner himself”.

In truth, the OGS press release was not very informative; its meaning was: an increase in seismic activity is observed; as we are not able to give an accurate interpretation, it is better to be alert. Nevertheless, it caused concern among the people and the government institutions decided to control the dissemination of scientific information.

3. Earthquake precursors of the 1976 Friuli earthquake?

Two particular phenomena characterized the period before 6 May 1976: the occurrence, during the winter before the earthquake, of some low-magnitude earthquakes in the Latisana area (Fig. 5), close to the Adriatic coast and about 50 km away from the epicentre of the main shock, and the recording of low-frequency interferences by the Marussi pendulums, located in the Grotta Gigante cave near Trieste, never recorded before or thereafter (Fig. 6). Both Latisana earthquakes and noise on the pendulums in the Grotta Gigante were interpreted as precursory phenomena of the Friuli earthquake (Chiaruttini and Zadro, 1976; Finetti *et al.*, 1979; Bonafede *et al.*, 1982, 1983), but they are still not fully understood.

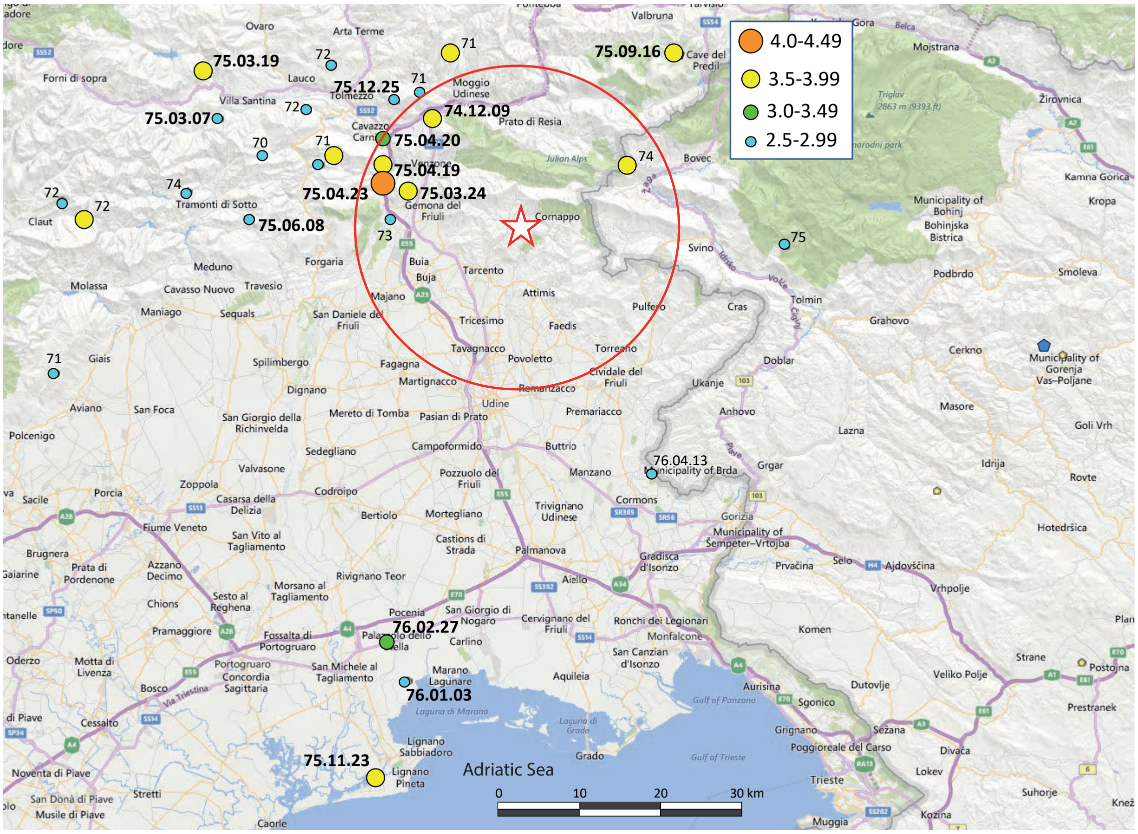


Fig. 5 - Map of the epicentres of the earthquakes in the period 1 January 1971 - 5 May 1976. The main shock of 6 May 1976 is marked with white star. The red circle has a 20-km radius and highlights a NW-ward sector where some events occurred in the two years preceding the 6 May earthquake. Three of the four Latisana "foreshocks" can be seen along the Adriatic coast; no reliable location is available for the fourth. The number associated with the epicentres identifies the date (year, month, and day; or only the year) of the event.

3.1. The Latisana "foreshocks" and the 1975 seismicity

In the period from November 1975 to February 1976, the Trieste seismological station recorded four earthquakes of low magnitude (M_L between 2.5 and 3.5) located near Latisana, along the Adriatic coast. Latisana is in an area considered almost aseismic and situated about 50 km away from the epicentre of the Friuli earthquakes (Fig. 5), not characterized by the presence of known faults (also at the current state of knowledge). Subsequent studies (e.g. Finetti *et al.*, 1979) considered these earthquakes as possible precursors of the 6 May 1976 earthquake, even in the absence of tectonic structures connecting the two areas (Slejko *et al.*, 1989). This interpretation was motivated by a slight asymmetric crustal undulation and the occurrence of the events was suggested as due to microfractures developing during an over-stress phase at the fold in the initial stage of a compressive deformation (Finetti *et al.*, 1979). Only a few other earthquakes of low magnitude in the Latisana area have been recorded since then by the regional seismometric network, operating in Friuli since May 1977.

On the other hand, during 1975, some earthquakes with magnitude between 3.5 and 4.0 have been recorded (Sandron *et al.*, 2014) in an area of 20 km away (red circle in Fig. 5) from the future 1976 main shock (white star). They are mainly located NW of the 6 May epicentre and quite

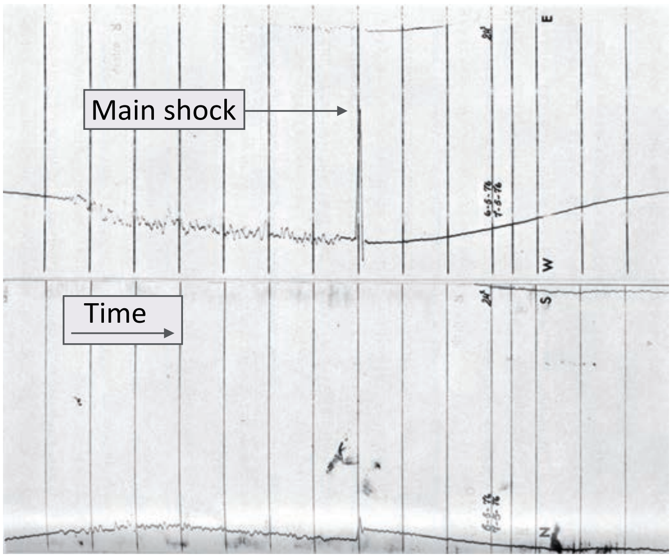


Fig. 6 - Transients recorded by the two horizontal components of the Marussi pendulum located in the Grotta Gigante cave near Trieste (after Chiaruttini and Zadro, 1976). The noise disappeared after the shock of 6 May 1976 (main shock in the figure). Parallel lines correspond to hours.

close in space and time. Starting from the north, the first event is the Amaro M_L 3.7 earthquake, which occurred on 9 December 1974. Then, on 24 March 1975, an M_L 3.9 seismic event happened slightly north of Gemona. Three events occurred in rapid succession around the Cavazzo Lake in April 1975: 19 April, M_L 3.6; 20 April, M_L 3.3; and the biggest one with an M_L of 4.0 on 23 April. Only a couple of events, with an M_L less than 3, occurred until the end of the year: the first on 8 June and the last on 25 December. No other events were recorded before 6 May 1976.

3.2. The Earth tide variations

Another phenomenon, possibly connected with the Friuli earthquakes, is represented by some anomalous oscillations recorded by the Trieste Earth tide station, located in the Grotta Gigante cave (Karst region around Trieste, about 70 km from the epicentre of the 6 May 1976 event). Regular oscillations with dominant period of several minutes, superimposed on the regular Earth tide cycle, were recorded by both components of the Marussi pendulum since 26 January 1973 (Chiaruttini and Zadro, 1976). They were rare during 1973, appearing more frequently in the following years and ceasing abruptly with the 6 May 1976 main shock (Fig. 6). Only on 20 May 1976, were weak disturbances again recorded, and ceased again after the second large shock of 15 September 1976. Similar oscillations did not occur in the following years (Carla Braitenberg, personal communication). Both creep and dilatancy phenomena were proposed initially as possible explanations (Chiaruttini and Zadro, 1976), while a kind of slow slippage at depth (silent earthquakes) was suggested by further studies as the source of the observed oscillations (Bonafede *et al.*, 1982, 1983). No further studies on the 1976 anomalous oscillations at the Trieste Earth Tide station have been undertaken since then.

4. Seismic pattern during the 1976 sequence

Although it is very likely that a final solution on the two mysterious "earthquake precursors" cited previously will be never discovered, it is interesting to investigate if the 1976 seismological data would have forecasted something using the present knowledge. The improved knowledge consists in the availability of different seismological data sets nowadays with respect to that of 1976.

The seismological data set available at the time of the 1976 earthquakes consisted of the 446 earthquakes with epicentre locations of the Trieste station (Colautti *et al.*, 1976; OGS, 1978), 395 of which also had a magnitude estimate, referring to the period 6 May 1976 to 5 May 1977. These locations and magnitudes were computed based on the seismograms recorded by the instruments of the Trieste World Wide Standardized Seismographic station: three components of the Benioff short period seismograph, three components of the Ewing-Press long-period seismograph, and two horizontal components of the Wood-Anderson torsion seismograph. In practice, distance and azimuth were calculated and reported on a map of Italy, in order to identify the epicentral area (therefore a very low accuracy of the location). Some events were also checked with the phase readings of the Ljubljana station. During the summer of 1976, a computer program was written in FORTRAN language and the distance and azimuth estimates were translated into geographical coordinates (Colautti *et al.*, 1976; OGS, 1978). Some temporary networks were deployed during the seismic sequence (see Slejko, 2018), but operated only for short time periods.

On 6 May 1977, the first three stations of the Friuli seismometric network started recording, which enabled producing better quality locations. In fact, a continuous recording was established and the seismic signals were sent to the central station in Udine, where they were recorded on magnetic tapes. The event detection was based on a visual inspection on an oscilloscope of the continuous recording and the detected events were printed on paper for the seismogram analysis. The epicentre location was performed initially by the EPIC (Bolt and Turcotte, 1964) and later by the Hypo71 (Lee and Lahr, 1975) computer codes. In December 1977, seven seismometric stations of the OGS network were operating in central Friuli.

To date, all available seismological data concerning the Friuli seismic sequence, from 6 May 1976 to 31 December 1977, have been collected and new locations have been computed.

4.1. The 1976-1977 epicentre locations

In the following decades, all available seismological data regarding the 1976 sequence have been collected and new elaborations have been performed (Renner, 1995; Poli *et al.*, 2002). On occasion of the 40th anniversary of the main shock, a new elaboration has been planned, aiming at fixing ultimately the space-time evolution of the sequence and the work is documented in this paper. More precisely, all phase readings from original seismograms and bulletins of public and private, permanent and temporary stations within a 250-km epicentral distance have been collected and integrated with the data reported in the website of the International Seismological Centre (ISC). The Hypo71 software (Lee and Lahr, 1975) has been used because the time accuracy and the space distribution of the stations (presence of stations in the epicentral area) do not require a more sophisticated location algorithm [e.g. the local source tomography used to determine 3D velocity images and earthquake locations also for the Friuli area (Amato *et al.*, 1990)]. Several crustal models have been considered; in the end, that of the European Mediterranean Seismological Centre Working Group on the Friuli Earthquakes (1976) has been selected, since it produced the most reasonable depth estimation, according to the tectonic information available, and the smallest statistical errors on the location. Several maximum epicentral distances have been tested as well, showing that the 250-km maximum distance over which the stations are not considered in the location gives the best performance.

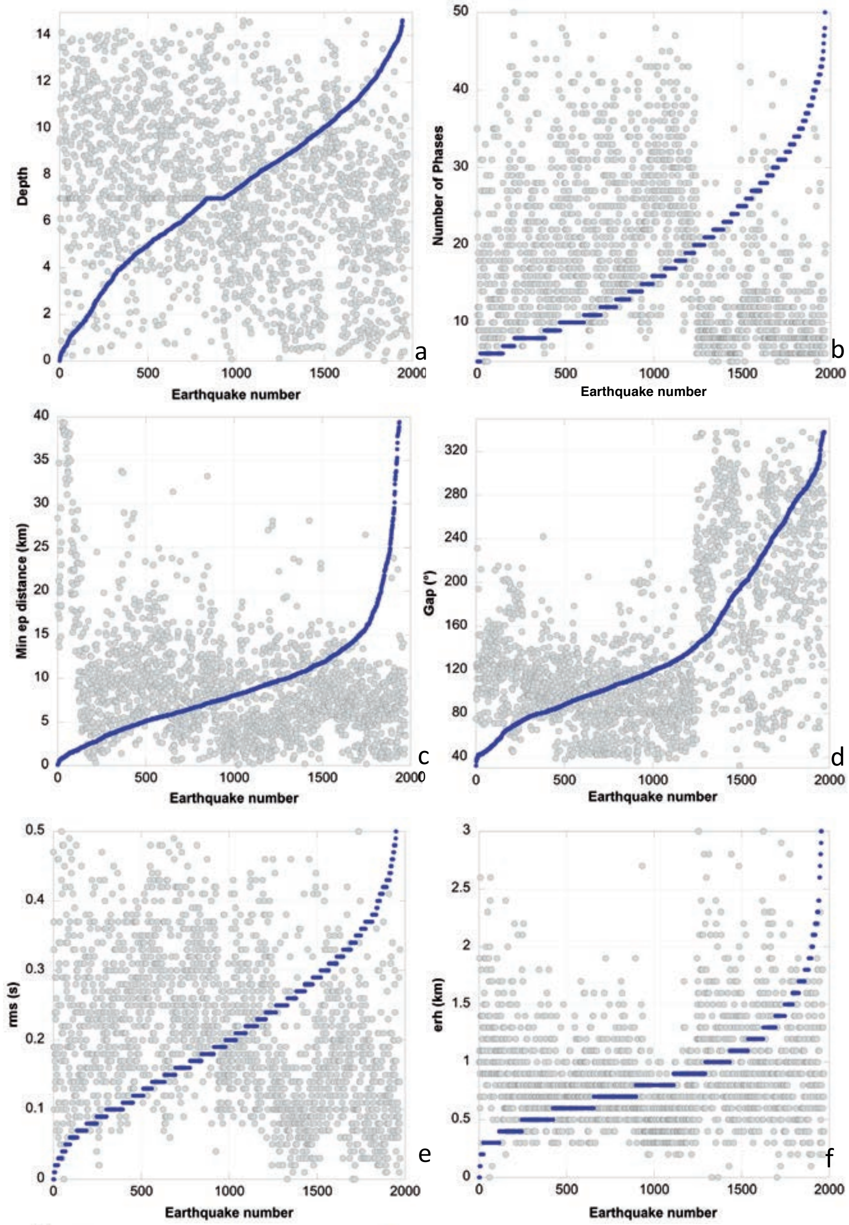
We have collected the data for 2061 earthquakes in the period from 6 May 1976 to 31 December 1977 (all locations are available in the electronic supplement). The data set was restricted to the area delimited by the corner coordinates 46.0°N, 12.8°E - 46.5°N, 13.5°E, which corresponds to the epicentral area in central Friuli of almost the total events of the sequence begun on 6 May. Locations with standard errors less than 1.0 s, 10 km, and 100 km, respectively for the origin time, the epicentre, and the focal depth were considered acceptable. Using these criteria, we obtained a set of 1971 locations that have been used for the following investigations. The majority of these events (1242 in the period 6 May 1976 to 5 May 1977) also have a duration magnitude (M_D) estimate, recomputed according to Rebez and Renner (1991). There are 429 events with a magnitude value that are both in the original (OGS, 1978) set and in new set of locations; these earthquakes have been used for the following comparisons between the two data sets.

Fig. 7 shows the main parameters identifying the quality of the obtained locations. The plots refer to the main bulk of the parameter estimates and, consequently, a few values have been omitted in the plots (the number of the missing data is reported in the figure caption). It can be seen that almost all locations are confined to the upper 16 km of crust (Fig. 7a) with a mean value of 7.4 km. The number of phase readings (mean value 18) has increased from 6 May 1976 to 5 May 1977 (no. 1242 in Fig. 7b) and decreased notably after that date, mainly because of the presence of the OGS stations of the Friuli network in and around the epicentral area, that guarantees good locations also for weak events, without the need for additional temporary stations. With the exception of the very few days when stations at a long distance also recorded the (strong) Friuli earthquakes, and in case of other strong events (Fig. 7c), the stations used for the hypocentre location are those of the near field (distance less than 20 km): the mean minimum distance for the whole period is 9.6 km. The azimuthal coverage was quite good during the first year (Fig. 7d); later, it became worse because of the presence of local stations (see Fig. 7b), that reduced the need for a large number of stations: the mean gap for the whole period is 142°. The error in the origin time is acceptable (mean value 0.23 s) over the whole data set (Fig. 7e), with a slight improvement with the deployment of the stations of the Friuli network on 6 May 1977. The error in the epicentre location (mean value 0.9 km) is generally less than 1.5 km (Fig. 7f) and it worsens after 6 May 1977. The error in the focal depth (mean value 2.2 km) is generally limited to less than 4 km, with a few events with a very large error, not reported in Fig. 7g.

With respect to the 479 locations of Poli *et al.* (2002), this improved data set of locations (1971 hypocentres) shows slightly lower standard errors of origin time and epicentre, while the error on the focal depth is slightly higher.

Concerning the magnitude, Fig. 8 shows the Gutenberg – Richter graph of the complete data set of events with estimated M_L magnitude. It can be seen that there is no completeness for quakes smaller than 2.8 and an evident shift from the linear trend for events with an M_L between 4.9 and 5.2, indicating a surplus of events in these classes. The interpolation according to the maximum likelihood approach gives a *b*-value of 0.93 (red line in Fig. 8), while that according to the least squares [mathematically not suitable for dependent data, see Slejko *et al*. (2008)] gives a *b*-value of 0.69 (blue line in Fig. 8).

The new location of the main shock of 6 May (see Slejko, 2018) practically coincides with that of Poli *et al.* (2002) and is quite close to several others (see Fig. 9), in a sector of the pre-Alpine foothills where there are no major towns or villages. This fact, perhaps, justifies the different locations (Giorgetti, 1976; Rovida *et al*., 2016) of the macroseismic epicentre, in an area populated



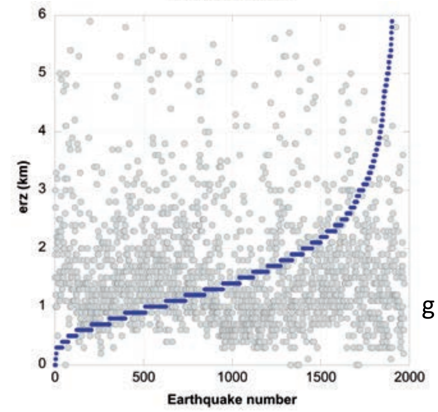


Fig. 7 - Statistics on the 1971 new locations with the progressive earthquake number (indication of the time occurrence of the event) on the x-axis: a) depth (mean = 7.4 +/-3.6 km; 28 out); b) number of phases (mean = 18 +/-10; 4 out); c) minimum distance (mean = 9.6 +/-7.9 km; 34 out); d) gap (mean = 142 +/-73°; 0 out); e) error in the origin time (mean = 0.21 +/-0.11 s; 22 out); f) error in the epicentre (mean = 0.9 +/-0.6 km; 15 out); g) error in the focal depth (mean = 2.2 +/-4.9 km; 66 out). Out indicates the number of events not reported in the picture. The blue line represents the ranked series (the minimum value is associated with the first event and the maximum with the last event).

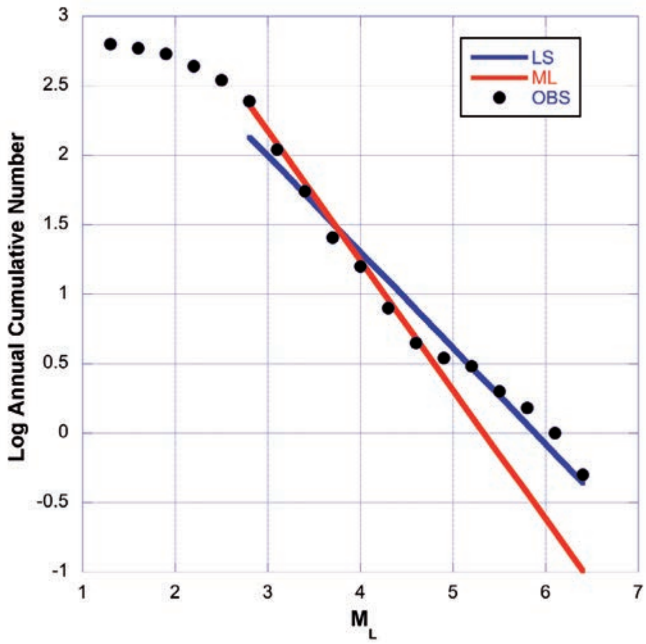


Fig. 8 - Gutenberg - Richter graph for the seismic sequence in Friuli from 6 May 1976 to 31 December 1977. The red line indicates the maximum likelihood fit while the blue line shows the least squares (matematically not suitable) fit. The black solid dots are the seismicity rates.

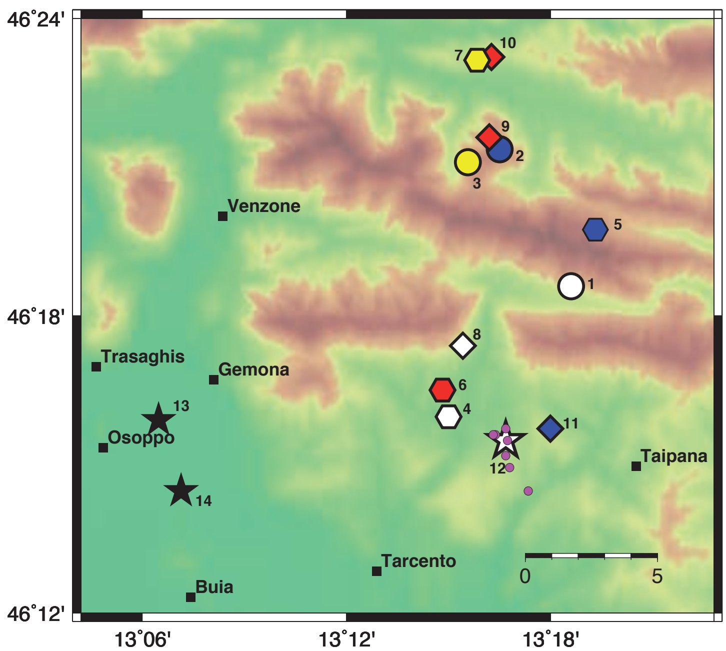


Fig. 9 - Epicentres of the main shock of 6 May 1976 according to different authors. Legend: 1 = hypocentral determination by the Centre Seismologique Europeo-Mediterraneen (CSEM), 2 = http://earthquake.usgs.gov, 3 = www.isc.ac.uk, 4 = Cagnetti and Pasquale (1979), 5 = Cipar (1980), 6 = Barbano *et al.* (1985), 7 = Engdhal *et al.* (1998), 8 = Aoudia *et al.* (2000), 9 = Pondrelli *et al.* (2001), 10 = Engdahl and Villaseñor (2002), 11 = Poli *et al.* (2002), 12 = Slejko (2018). The solid magenta dots show alternative solutions obtained with different crustal models and parameters. The two black stars indicate macroseismic epicentres: 13 = Giorgetti (1976), 14 = Rovida *et al.* (2016). Two areas remain broadly identified: the foothills of the Julian Alps east of Gemona (nos. 4, 6, 8, 11, 12) and the Val Resia NE of Venzone (nos. 2, 3, 7, 9, 10). Only two locations (nos. 1 and 5) placed the epicentre in the Musi Mountains area (from Slejko, 2018).

by the three towns of Gemona, Trasaghis, and Osoppo. The southern position of this new location with respect to some others (e.g. Enghdal and Villaseñor, 2002; Pondrelli *et al.*, 2001), could be motivated by new data referring to local stations, used before only in part by Poli *et al.* (2002).

4.2. The different picture of the 1976-1977 seismicity

As cited before, the events of the Friuli sequence were originally located (Colautti *et al.*, 1976; OGS, 1978) using the data of the Trieste seismological station (distance and azimuth): this procedure implies possible large epicentral errors and artificial alignments (Fig. 10a). The map with the re-localizations of the same 429 events done in this study (Fig. 10b) shows a more diffuse pattern. To better highlight the difference in the two data sets, a further elaboration has been produced, subdividing the study region into 2.5 km wide square cells where the number of events is counted (top panels in Fig. 11) and the total energy release is computed (bottom panels in Fig. 11). It can be seen that the bulk of seismicity remains more clustered in the re-elaborated locations and a NW-SE elongation appears for the main energy release (Fig. 11e).

Aiming at analysing the kind of error associated to the original locations (accepting that the revised ones are error free), the difference in distance and azimuth between the two sets of solutions has been explored (Fig. 12). Considering the difference in distance (absolute value) with respect to the location of the Trieste station, it is possible to see that the 50th percentile refers to a value of 12 km and 90% of the locations have less than a 20 km difference (Fig. 12a). In detail (Fig. 12b), it can be noted that the distance calculated originally is generally larger than the re-calculated one: the modal value is 6-8 km. Considering the differences in azimuth, calculated with respect to the Trieste station, a bimodal distribution, with the highest peak at 8°, can be seen: this means that the original locations are slightly shifted eastwards (Fig. 12c). Finally, a cumulative analysis for distance and azimuth is reported in Fig. 12d, where the re-locations are shown with respect to the original ones, placed at the centre. Although the new locations fall within all the four quadrants, the majority of them refer to a shift within 20 km in the E/ENE direction.

The significance of the analysis described here lies in a possible answer to the question whether the seismological data available at the time of the 1976 sequence were or were not suitable to identify a hypothetical anomalous pattern before the strongest events of the sequence itself. The amount of error associated to those locations (compare Figs. 6a and 6b), accepting that the new ones are sufficiently precise (still to be demonstrated), marks them as affected by large uncertainties and, consequently, hardly suitable to identify modest space variations.

5. Searching for a forecasting clue

As mentioned in the introduction, the aim of this paper is also to investigate if some clues in the seismological data set could have pointed to the occurrence of a strong forthcoming event. Only the space evolution in time of the epicentres is considered here, while a complete analysis should also investigate other seismological and geophysical parameters.

In this study, three periods have been investigated: before the main shock of 6 May 1976; before the strong aftershocks of 11 and 15 September 1976; and before the last strong aftershock of 16 September 1977.

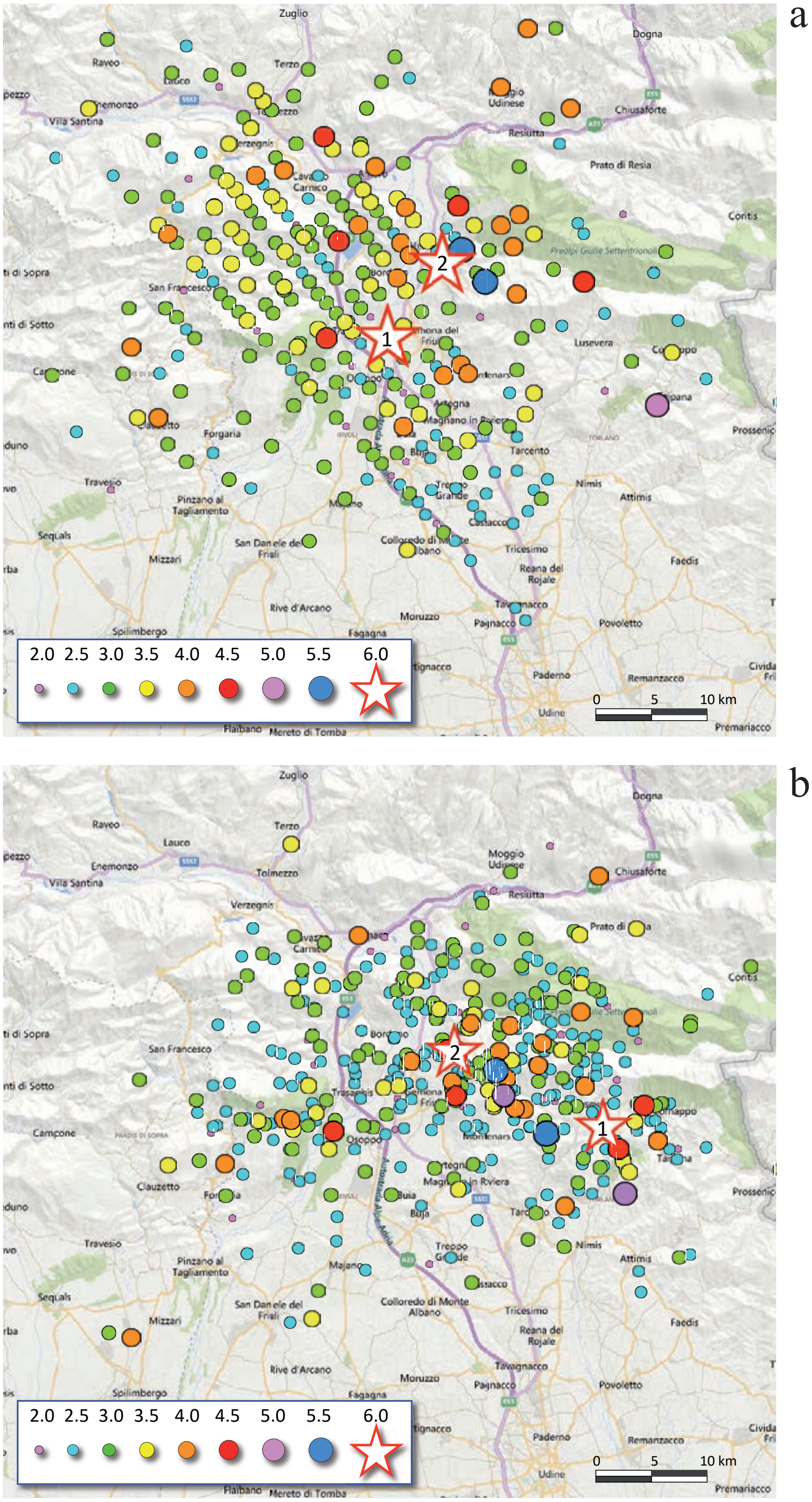


Fig. 10 - Space distribution of the events of the Friuli seismic sequence: a) original locations (OGS, 1978) for the period 6 May 1976 – 5 May 1977; b) re-locations of the same events. c) re-locations of all events of the period from 6 May 1976 to 31 December 31, 1977. The stars indicate the event of 6 May 1976 (no. 1) and the main event of 15 September 1976 (no. 2).

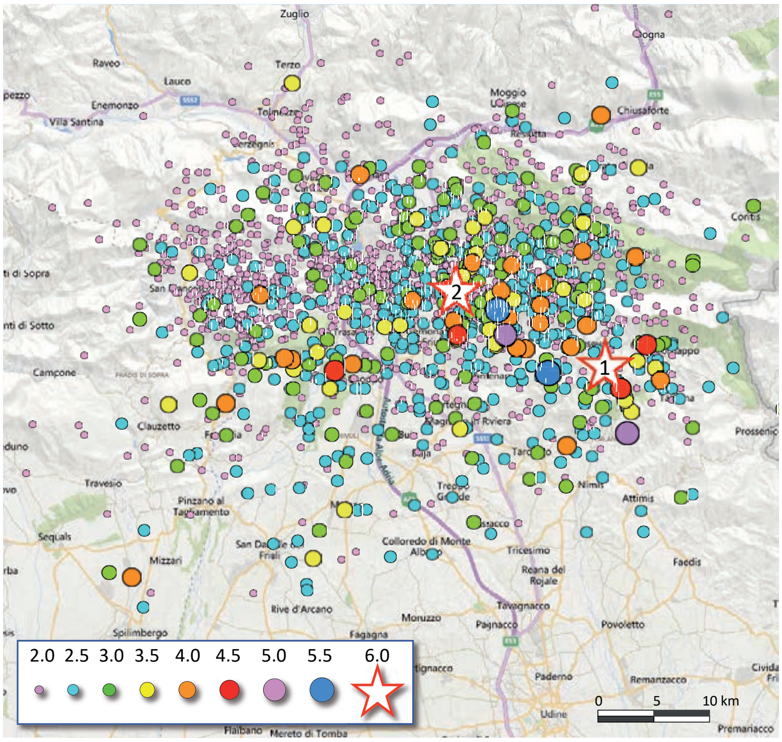


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Fig. 10 - continued.

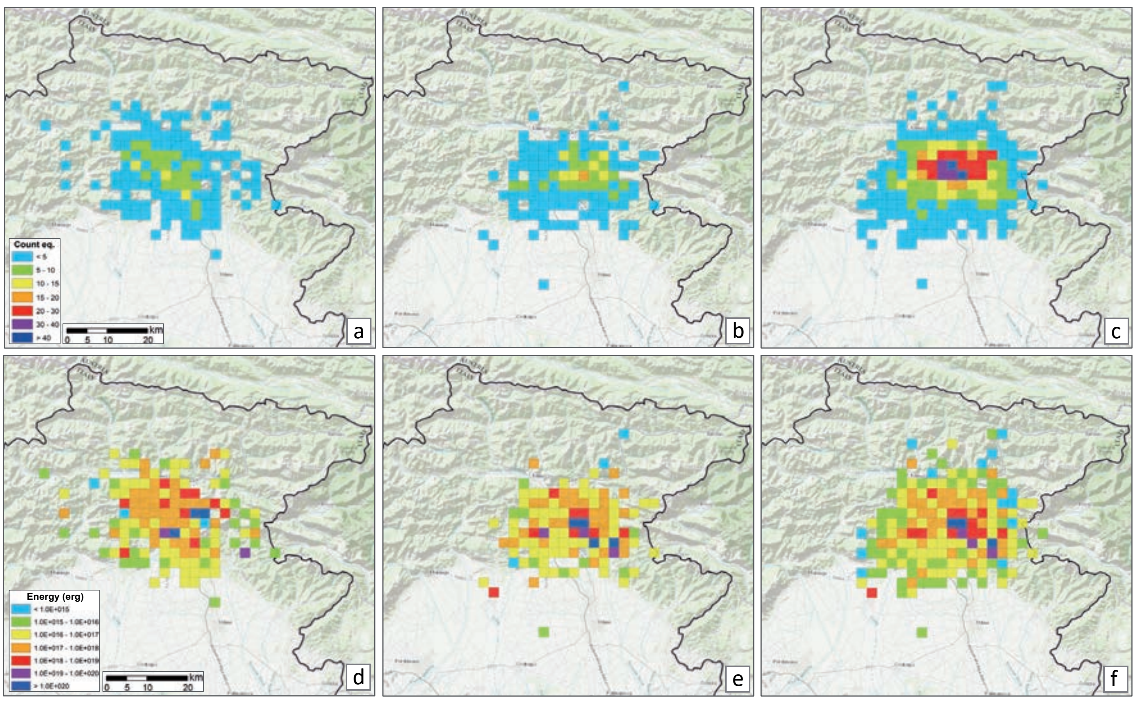

Fig. 11 - Comparison between the original (OGS, 1978) and revised locations for the period 6 May 1976 – 5 May 1977 in terms of cumulative number of events (top panel) and total energy release (bottom panel): a and d) original (OGS, 1978) 429 events common to both data sets; b and e) re-locations of the 429 common events; c and f) re-locations of the whole data set of the present work (6 May 1976 to 31 December 1977).

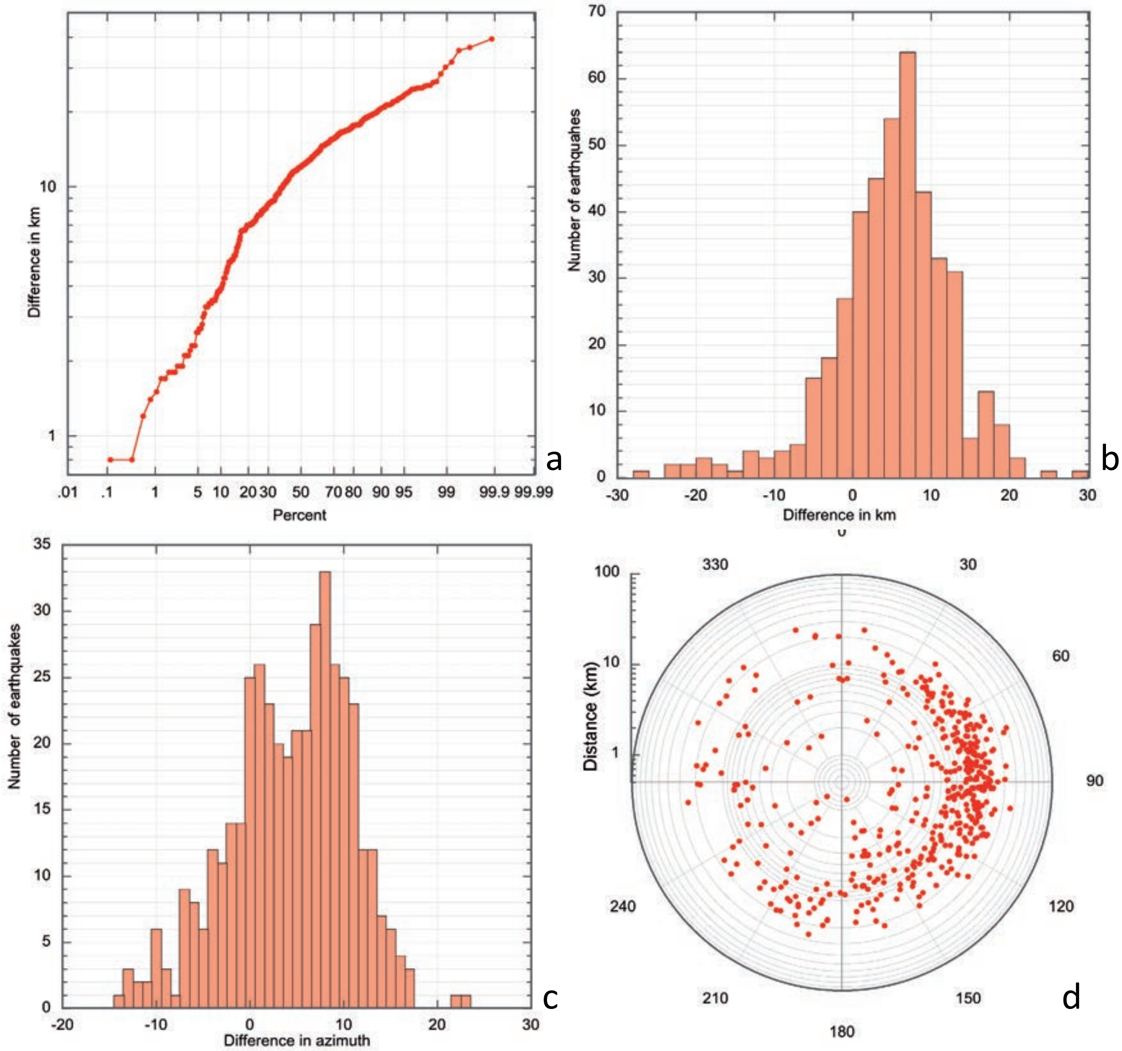

Fig. 12 - Comparison between the original locations (OGS, 1978) and the present re-locations for the earthquakes in the time period 6 May 1976 to 5 May 1977: a) statistical distribution of the distance (km) between the original localization and the re-locations; b) distribution in bin classes of the difference in distances (original distance from the Trieste station minus new distance from the Trieste station); c) differences in azimuth between the new re-locations and the original ones with respect to the Trieste station (original azimuth from the Trieste station minus new azimuth from the Trieste station); d) distance and azimuth polar plot of the re-locations with respect to the original ones, placed at the centre of the plot.

5.1. Before the 6 May 1976 earthquake

This period is the most problematic to investigate, as the data from permanent stations are the only available ones (see Santulin *et al.*, 2018). Fig. 13 shows the space and time distribution of the earthquakes which occurred in a broader region around the 6 May 1976 epicentre (the area shown in Fig. 5), for the period from January 1971 to 5 May 1976. It can be seen that the seismicity was stronger in 1975 than before (Fig. 13b); and, since 1974, the activity affected areas quite close (distances less than 20 km) to the future epicentre of the earthquake of 6 May (Fig. 13a). These last events are also illustrated in Fig. 5, where it can be observed that almost all of them occurred

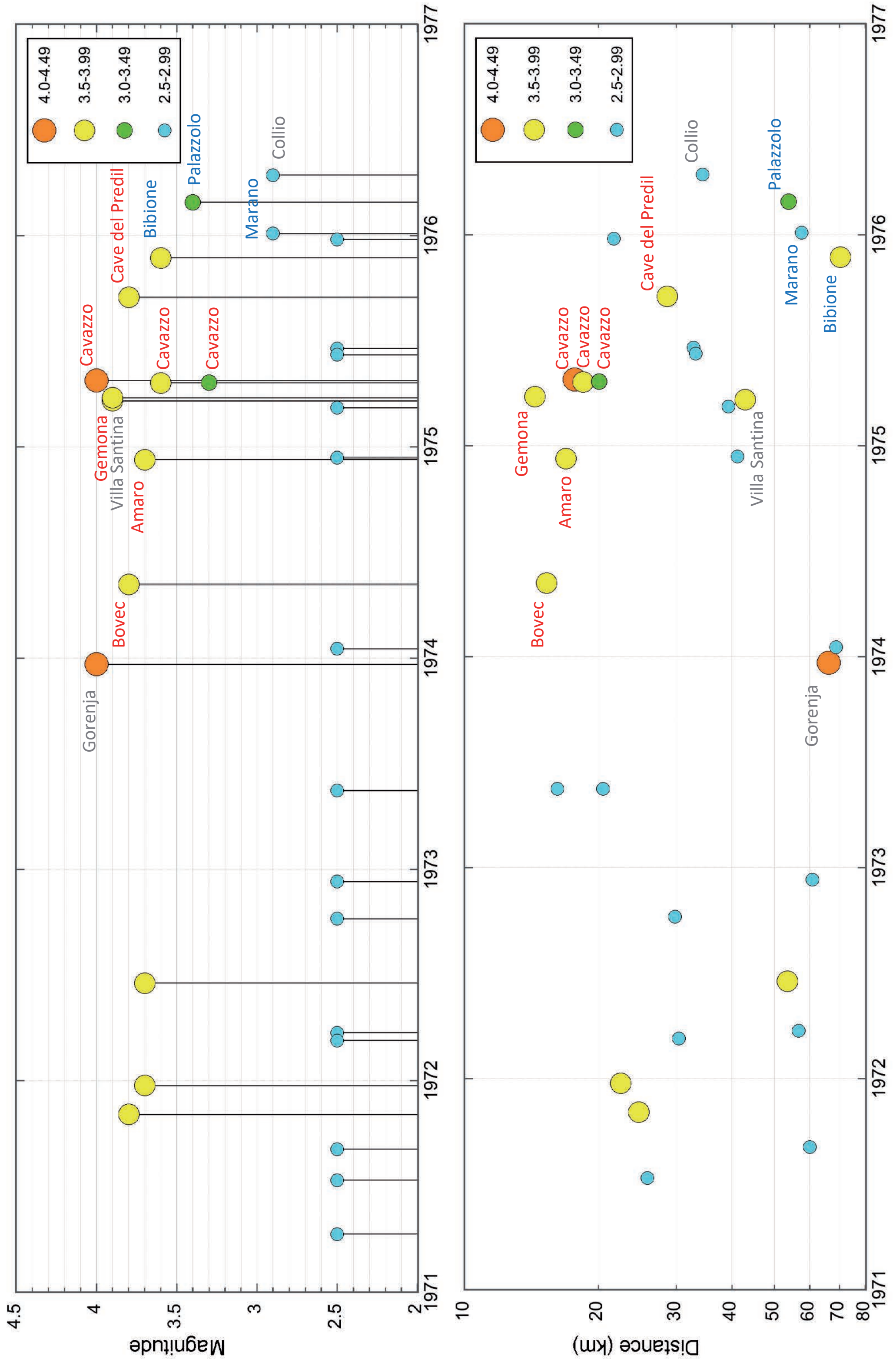

Fig. 13 - Time evolution of the seismicity in Friuli and adjacent areas from 1 January 1971 to 5 May 1976: magnitude (top panel) and distance from the epicentre of the 6 May main shock (bottom panel).

NW of the 6 May epicentre. As noted, only three of the four quakes around Latisana (labelled in light blue in Fig. 13b) in the winter 1975 – 1976 are reported in Fig. 5, because it was not possible to locate the forth one with the available station readings (the only estimate of the location is based on the distance and azimuth of the Trieste station).

No clear evidence can be found, then, on the incoming 6 May earthquake based on the available seismological data.

5.2. Before the September 1976 strong aftershocks

After the almost aseismic period of July and August 1976, an increase in seismicity occurred at the beginning of September (Fig. 14a), followed by the seismic crisis characterised by two strong aftershocks on 11 (M_L 5.2 and 5.6) and a further two on 15 September (M_L 5.8 and 6.1), together with several low magnitude events in between and after. This behaviour is highlighted by the change in the slope of the graph of the cumulative number of events in Fig. 14.

Additional information is provided by the maps in Fig. 15, where the total released energy is reported for different time periods. The activity in July, August, and September before the two

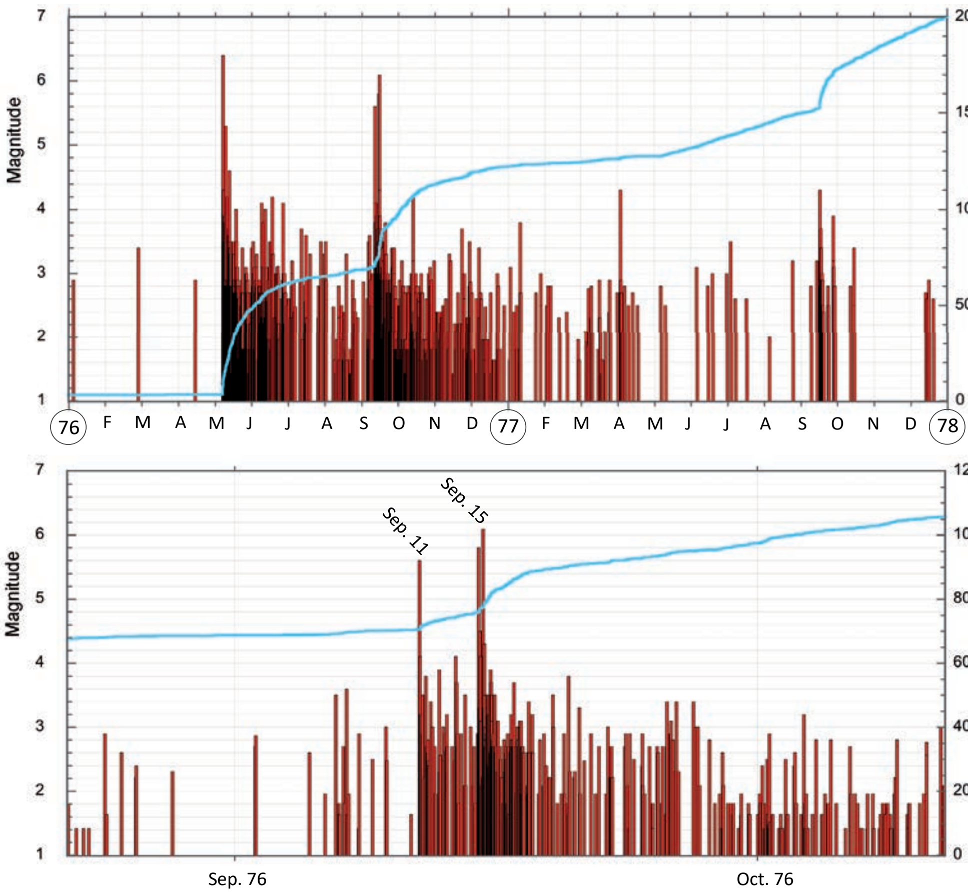

Fig. 14 - Evolution of the seismicity in Friuli during the whole seismic sequence (top from 1 January 1976 to 31 December 1977) and during the aftershock sequence of September 1976 (bottom from 1 September to 31 October 1976: enlargement of the upper plot. The bars indicate the magnitude of the events, the solid blue line the cumulative number of events. An increase of the slope of the curve of the total number of events can be seen at the beginning of September 1976, and more sharply during the crisis of 11 and 15 September 1976.

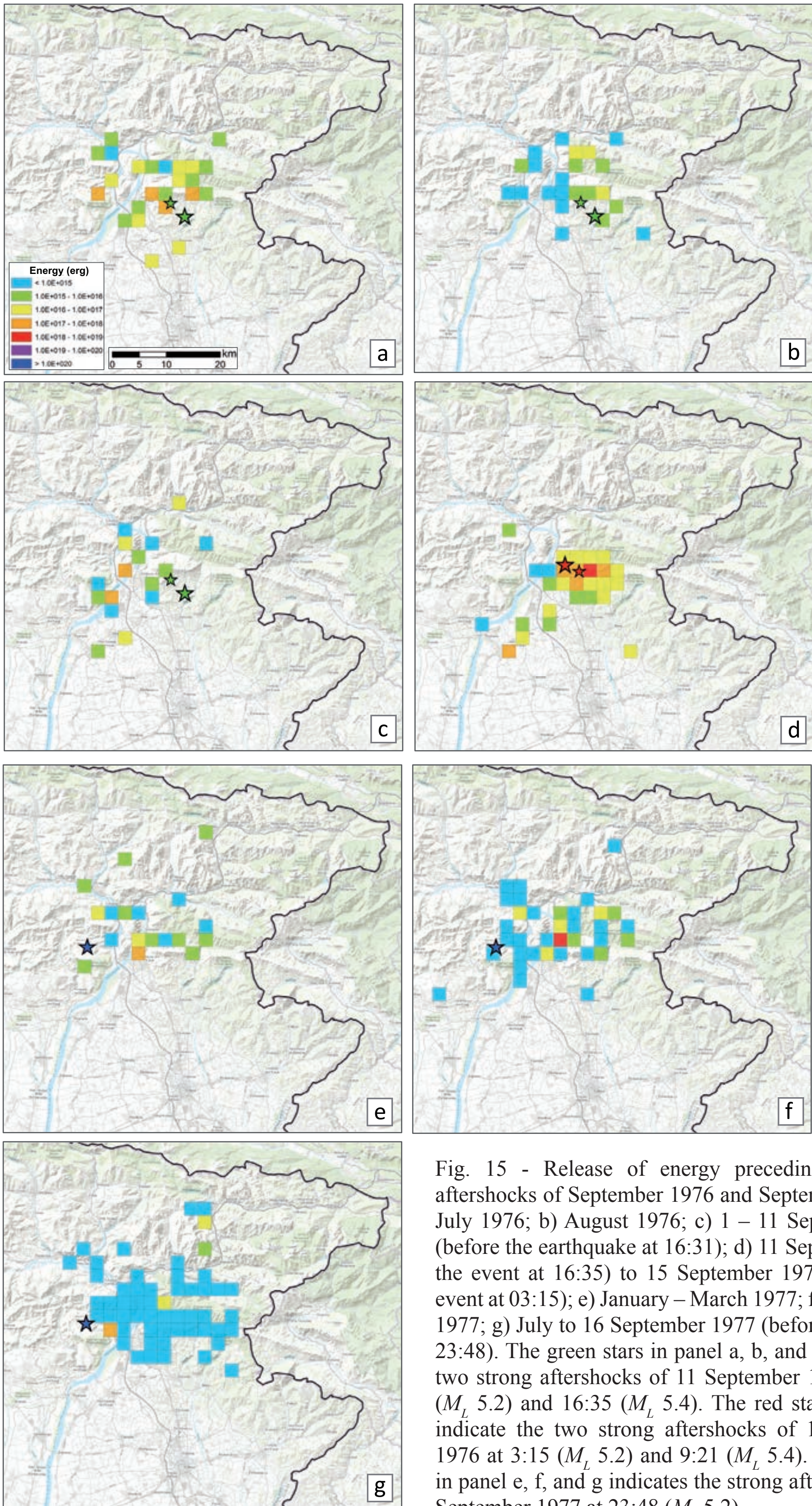

Fig. 15 - Release of energy preceding the strong aftershocks of September 1976 and September 1977: a) July 1976; b) August 1976; c) 1 – 11 September 1976 (before the earthquake at 16:31); d) 11 September (after the event at 16:35) to 15 September 1976 (before the event at 03:15); e) January – March 1977; f) April – June 1977; g) July to 16 September 1977 (before the event at 23:48). The green stars in panel a, b, and c indicate the two strong aftershocks of 11 September 1976 at 16:31 (M_L 5.2) and 16:35 (M_L 5.4). The red stars in panel d indicate the two strong aftershocks of 15 September 1976 at 3:15 (M_L 5.2) and 9:21 (M_L 5.4). The blue star in panel e, f, and g indicates the strong aftershock of 16 September 1977 at 23:48 (M_L 5.2).

shocks of the 11th is reported in Figs. 15a, 15b, and 15c, respectively. The two green stars indicate the two events of 11 September. No evidence of clustering of energy release can be seen and the activity remains distributed in a wide area around the epicentre of 6 May. Fig. 15d shows the energy release after the two events of 11 September and before the other two of 15 September. In this case, a clear concentration of released energy can be seen very close to the epicentres of the two quakes of 15 September, indicated by the two red stars.

This space behaviour has been investigated by a suite of further plots, where the variations in latitude, longitude, and distance is displayed (Fig. 16). None of the plots in latitude (Figs. 16a, 16b, 16c), in longitude (Fig. 16d, 16e, 16f), and in distance from the M_L 6.1 15 September aftershock (Fig. 16g), show a tendency for the epicentres to converge towards the location of the 11 September events. Conversely, the plots referring to mid-September (Figs. 16b, 16e) show an evident migration of the seismicity towards the epicentres of 15 September, which are close to each other.

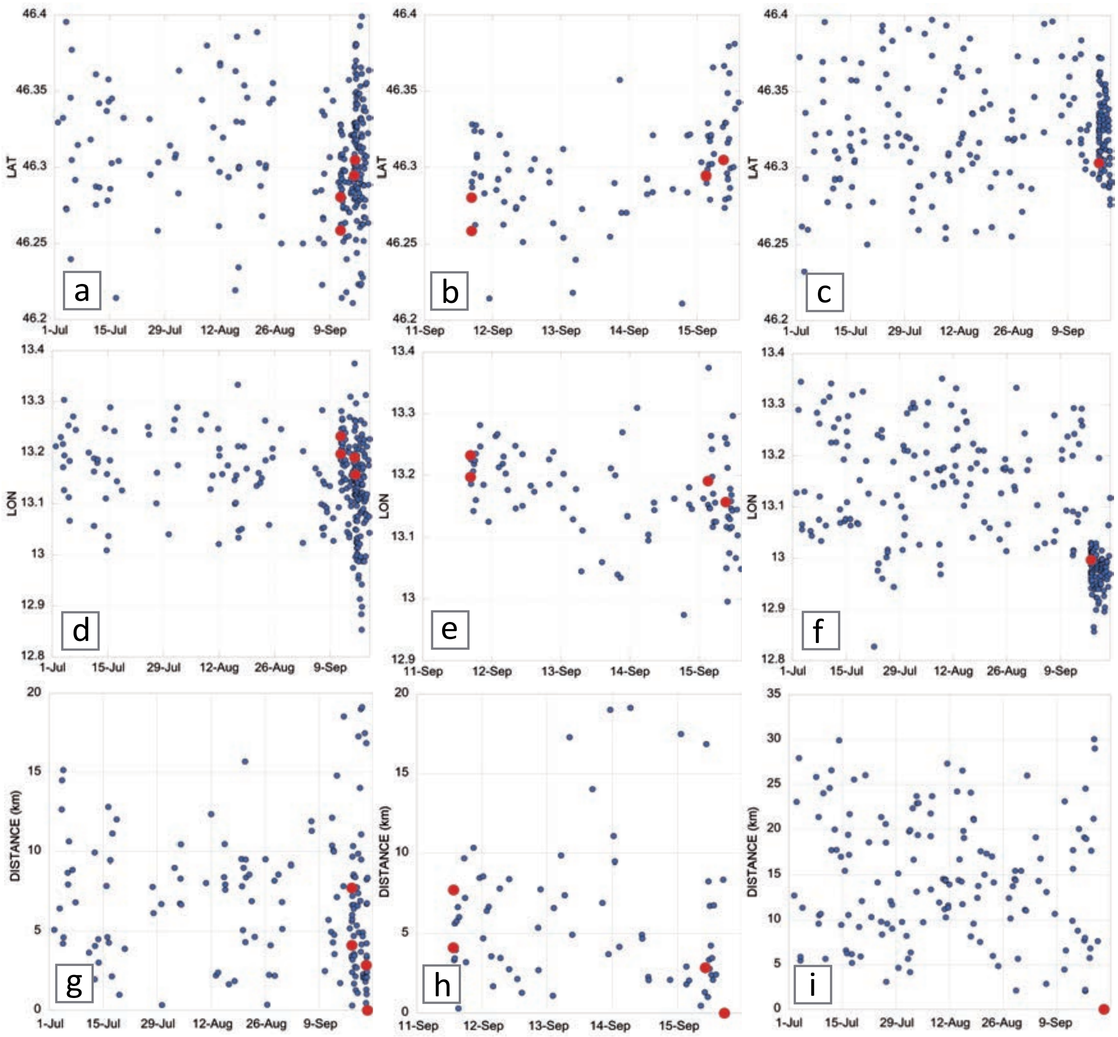

Fig. 16 - Space evolution of the Friuli sequence in latitude (a, b, c), longitude (d, e, f), and distance (g, h, i) from 1 July to 16 September 1976 (a, d, g), from 11 to 16 September 1976 (b, e, h: enlargement of the previous panels), from 1 July to 17 September 1977 (c, f, i). The red dots identify the four strong events of September 1976 (M_L 5.2 and 5.4 on 11 and 5.8 and 6.1 on 15) and that of September 1977 (M_L 5.2).

5.3. Before the September 1977 strong aftershock

The following considerations on the 1977 seismicity are based on the data recorded by the OGS seismometric network of Friuli, which consisted of 7 stations at the beginning of September 1977.

It is not actually clear if the event of 16 September 1977 with an M_L 5.2 can be considered an aftershock of the 6 May 1976 earthquake or not; nevertheless, as we are only interested in a possible migration of the seismicity towards the new epicentre, we have included it in the aftershock sequence.

Figs. 15e, 15f, and 15g refer to the M_L 5.2 earthquake of 16 September 1977, respectively for the first three months of 1977, the second ones, and September before the strong aftershock. A weak indication of westward epicentre migration can be noted, especially in the activity in the days before the event but, in general, seismicity continued to involve the entire epicentral area of the sequence.

More problematic, instead, is the interpretation of the plots showing the behaviour in latitude (Fig. 16c), longitude (Fig. 16f), and distance from the 16 September 1977 event (Fig. 16i) because, although the epicentres are spread over large distances, a certain tendency of moving towards the epicentre of the M_L 5.2 event appears.

6. Conclusions

We could say that two rather similar communications on the evolution of a seismic sequence led to opposite results: the director of the Ljubljana Observatory became a hero for the media for having "forecasted" an earthquake, while the director of the Trieste Observatory was reprimanded by the governmental authorities for a false alarm. The seismic sequence of L'Aquila, with the following trial for the members of the national seismic committee managing great risks, is an even more evident example of the difficulties of the scientific institutions in communicating properly. As this event was already extensively described in the literature (e.g. Alexander, 2014; Cocco *et al.*, 2015; Stucchi *et al.*, 2016) it is not considered here.

A question arises: is there any further scientific aspect of the seismic process that scientists should consider before disseminating information? Again, the example of the Friuli earthquake could help answer this question. In fact, the equipment operating at that time highlighted two particular aspects, which were studied later but without definitive results.

Looking for any clues indicating a possible earthquake arrival, we have analysed the seismicity recorded before the 6 May 1976 main shock and the following long seismic sequence based on a data set of re-located events, aiming at identifying any possible space migration of seismicity towards the location of the incoming earthquake. Only in the case of the events that followed the two strong aftershocks of 11 September 1976 and preceded those even stronger ones of 15 September, can a tendency of grouping towards the location of the incoming quakes be tentatively proposed.

The example of the Friuli earthquake sequence does not support the possibility of any forecast based on precursor seismological signals. The increment of local seismicity should be considered with attention, although it was not a robust piece of evidence in the case of the 1976 sequence. The collection of seismological data was not detailed at the time when the Banja Luka earthquake occurred and, consequently, no analyses are available about a possible peculiar pattern of the seismicity. It is important to remember that the only positive (and useful) seismic prediction refers to the magnitude 7.3 earthquake that struck Haicheng in China in 1975. Although other anomalous phenomena that occurred in months previous to the earthquake were identified later, the prediction was based on the observation of a noticeable increase of the local seismicity, both in terms of number of events and magnitude, on the day immediately preceding the disastrous earthquake.

This observation motivated a seismic alarm and evacuation of the area subsequently affected by the disastrous earthquake [for a complete review of the Haicheng alarm, see Wang *et al.* (2006)].

At the present stage, earthquake generation still remains a mysterious process and, although new science produces continuous and important improvements in the knowledge of seismicity, the optimism of the 1970s, when earthquake prediction seemed a feasible result in a couple of decades, has faded away. Moreover, a wrong alarm, which is a very frequent situation, can cause more damage than the actual occurrence of an earthquake, if of small magnitude. On the other hand, a correct alarm can save many human lives, and this must be the main goal of research. The wish of the people to be properly informed about a possible incoming danger is, then, well motivated, but this is extremely difficult for the scientists, who currently can have only a vague idea of an incoming earthquake. The two reported examples illustrate well the puzzling dilemma that seismologists have to face.

It is obvious, then, that the right way to reduce seismic risk is to construct and retrofit buildings according to the building code, the only efficient procedure available nowadays.

Supplementary material related to this article, i.e. the earthquake locations for the sequence 1976-1977, is available online at the BGTA website www3.inogs.it/bgta.

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