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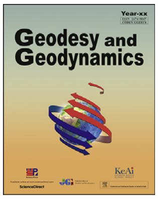

Intensities of ancient earthquakes, earthquake magnitude and soil dynamics effects. Evidence from the 1750 Croatia earthquake

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ABSTRACT

A problem in the study of pre-instrumental earthquakes is how to reconstruct their parameters based on usually fragmentary evidence of seismic intensities, which reflect the combined effect of fault dynamics, of radiation of seismic waves, and of local amplification or attenuation of strong seismic motions. This problem is highlighted in the 1750 earthquake in Croatia, in the active compressional margin of NW Adriatic, an area with rarely known seismic history. Recent high-quality historical and archaeological data revealed that the 1750 earthquake was associated with high (up to VIII) seismic intensities, which were assigned to local amplification of strong motion generated by a magnitude 5 earthquake. This scenario points to a nearly aseismic plate boundary and to an unusually long meizoseismal zone for a small earthquake. On the contrary, in this study, the 1750 earthquake is associated with a segment of a major thrust and with a $M > 6.0$ earthquake which produced moderate accelerations. These results were based on a triple correlation between (1) a Finite Fault Model derived from elastic dislocation analysis of differential subsidence of submerged coastal notches, (2) a major composite thrust and (3) the distribution of areas of high seismic intensities. This result provides some input for the estimation of the seismic hazard/risk in the study area, indicates that the Adria-Eurasia collision front in NW Croatia is not essentially aseismic, and highlights the need to include soil dynamics effects in the study of palaeoseismic events.

1. Introduction

The 2011.03.11 *M*w9.1 Tohoku (Japan) earthquake and the 2017.11.12, *M*w7.3 Iran–Iraq earthquake are two recent events which highlight the problem of underestimation of the maximum magnitude of earthquakes expected in various regions. A solution of this problem requires expanding the time interval of non-instrumental seismological observations which are necessary to provide reliable estimates of the maximum magnitudes of expected earthquakes and of the seismic hazard and risk in various regions. Analysis of historical records is the simplest approach for that in many parts of the world [1,2]. However, the efforts at expanding the length of records of pre-instrumental earthquakes face two limitations:

First, many events may be missing from earthquake catalogs; for example earthquakes not producing surface faulting and important ground deformation are not usually be recorded by typical, geology-oriented palaeoseismic studies [3], while strong earthquakes can be missed for various reasons, even in regions with a rich historic record. These may give the wrong impression of broad aseismic areas [4].

Second, literary evidence of earthquakes is usually recorded in major towns and in cultural, military or commercial centers, giving the impression that historical earthquakes selectively occur around such areas [1]. In addition, the destructive effects of earthquakes are dominated by the strong motions generated by the fault rupture and which are subsequently modified by local soil dynamics effects (soil amplification and topographic local aggravation or on the contrary attenuation of seismic ground accelerations [5,6]. Reports of damage and of the feeling of the strong motion in antiquity, roughly expressed by seismic intensities, are usually limited and

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may have a fragmentary character producing biased perceptions of the characteristics of the ancient earthquakes.

This problem is highlighted in the following two recent examples. The 2017.08.21 *M*4.0 earthquake in Ischia Island (Naples, Italy) produced death toll and localized major destruction [7], while the shallow, 2014 *M*6.9 earthquake in the North Aegean, at the extension of the North Anatolian Fault, produced very limited ground shaking and practically no damage close to its epicenter, but increased intensities about 50 km away from the fault [8]. Hence, if the Ischia earthquake had occurred some centuries ago, its damage reports would have probably been interpreted as evidence of a much stronger earthquake (biased result). On the contrary, the North Aegean earthquake would have been practically ignored (missed event), and if recorded, it would have been interpreted either as a smaller magnitude event, or as a rather remote event (biased result). These cases are definitely not unusual, because some of the major seismic destructions in the last 50–60 years, for example the 1960 Agadir (Morocco), the 1963 Skopje (FYR of Macedonia) and the 1999 Athens (Greece) earthquakes were associated with moderate earthquakes ($M \leq 6.0$) and with no significant signs of seismic surface faulting [6,9].

Hence, a requirement for a reliable analysis of the seismic risk and hazard is to know whether and how it is possible to combine the seismological, geological and engineering characteristics of earthquakes of the pre-instrumental period.

This article examines this problem focusing on the 1750 century earthquake in Croatia. Based on a combination of coastal palaeoseismic and tectonic data and Finite Fault Modeling on one hand, and on the other hand, on detailed historical and archaeological information for seismic damage, two alternative scenarios for this event are examined: a small (~*M*5) earthquake with intensities amplified due to soil dynamic effects, and a strong ($M > 6.0$) earthquake (preferred scenario).

This analysis bridges approaches of two different communities of scientists (seismologists/geologists/geodetists and earthquake engineers) and permits to arrive at conclusions concerning the expected maximum magnitude of earthquakes in the study area. Apart from this methodological contribution, this article presents data, results and arguments to be used for the analysis of the seismic risk and hazard in the study area. In addition, it provides also evidence to understand whether the plate boundary in Northern Adriatic (Fig. 1) is essentially aseismic or not.

2. Tectonic and geodynamic background

The coastal front of Croatia corresponds to a plate boundary accommodating the convergence between Eurasia and Adria, with a rate of about 2 cm/yr [10,11], which corresponds to about 10 m in the last 500 years. In the NW part of coastal Croatia this convergence is accommodated by a few major thrusts, especially the Vinodol-Bakar Thrust, a major composite thrust which is expressed in the topography as a long and narrow tectonic depression in carbonate rocks (Fig. 2a, [12]). Clustering of small instrumentally derived earthquakes indicates that this front is seismically active [17].

However, seismicity in this area is poorly known, and although some authors argue for strong historical earthquakes, no clear evidence for them had been documented till recently. Lack of important seismicity is a major problem, because moderate (~*M* 5.0) earthquakes can explain only a minor part of the convergence, and hence tend to indicate an essentially aseismic convergence front. This is quite unusual, although aseismic processes are known for certain compressive margins [14,15].

In the last years, however, new evidence on the seismicity of this critical area has been presented. Stiros and Moschas (2012) [16] provided evidence of recent reactivation of the Vinodol-Bakar Thrust and of strong ($M > 6$) earthquakes based on elastic dislocation analysis of the differential subsidence of coastal notches mapped in the Rijeka-Bakar area [12,17]. Herak et al. (2017) [18] on the other hand, based on historical seismicity data, rejected the possibility of earthquakes with magnitude M > 5 in the area in the last 500 years (Fig. 3). This result suggests an essentially aseismic collision front (i.e. that most of the 10 m plate convergence was aseismic).

3. The 1750 earthquake-previous approaches

The 1750 earthquake was included in various databases, but it remained an unclear event. Based on detailed historical (archival) and archaeological data (inscriptions), Herak et al. (2017) [18] documented seismic intensities for several towns produced by this earthquake. Their data are summarized in Figs. 3 and 4 and indicate that intensities ranged up to VIII (MSK scale) in Bakar. Intensities of the order of VII + were observed in the Rijeka harbor which was refurbished a few years after the earthquake, probably after some small coastal subsidence [16], while intensities of the order VII are inferred along a distance of about 40 km (Fig. 4). These authors noticed also that the wider meizoseismal area is located in a carbonate platform characterized by karst structures of different scales, often very narrow and elongated basins, controlled by nearly NW striking faults. Such karstic basins are filled with soft, unconsolidated deposits and host some of the important towns in the area.

Since amplification of seismic accelerations is expected in sediment-filled basins ([19],Fig. 2b and c), it was concluded that the inferred high (VII-VIII) macroseismic intensities for the 1750 and previous earthquakes reflect amplification of seismic accelerations in isolated karst valleys, generated by a moderate, ~*M*5 earthquake. A similar upper limit was proposed for the magnitude of all other earthquakes which have hit the area in the last 500 years (Fig. 3).

4. The 1750 earthquake: finite fault modeling and implications

Carbonate coasts in the wider Rijeka area are characterized by notches usually drowned at the depth of ~55 ± 3 cm. In the Rijeka-Bakar area the notch depth increases to about ~110 cm [12,17]. These notches have been the focus of study of various investigators [13] but a realistic scenario is that they represent relicts of a single notch formed probably during or after the Roman times at mean sea level. This single notch was formed or preserved where lithological conditions permitted, and subsequently, it was drowned by about 55 cm on the average, probably because of regional sea-level rise. In the wider Rijeka- Bakar area, along a distance of >20 km, the already submerged notch was subject to additional, differential subsidence up to 60 cm. This differential subsidence has a clear pattern (gradual increase to the NE; Fig. 4) and this can only indicate a tectonic, most probably seismic dislocation [16,21].

The observations of tectonic subsidence of the notch (summarized in terms of contours in Fig. 4) were used as input in an elastic dislocation analysis to compute the parameters of the fault (of a Finite Fault Model) responsible for these dislocations, in analogy to geodetic dislocations used for modeling faults [8,16,20]. A Finite Fault Model represents a 3-D representation of one or more orthogonal (planar) fault surfaces which are responsible for the observed ground deformations. Each fault surface is defined by nine parameters, corresponding to the size (fault length and width), the orientation (strike), the dip, the location (coordinates of the fault center), the depth and the sense of slip (rake and amount of slip, at a first approximation uniform for the whole fault segment) of the causative fault. More than one finite fault may be assumed to explain the observed deformation on the basis of the elastic

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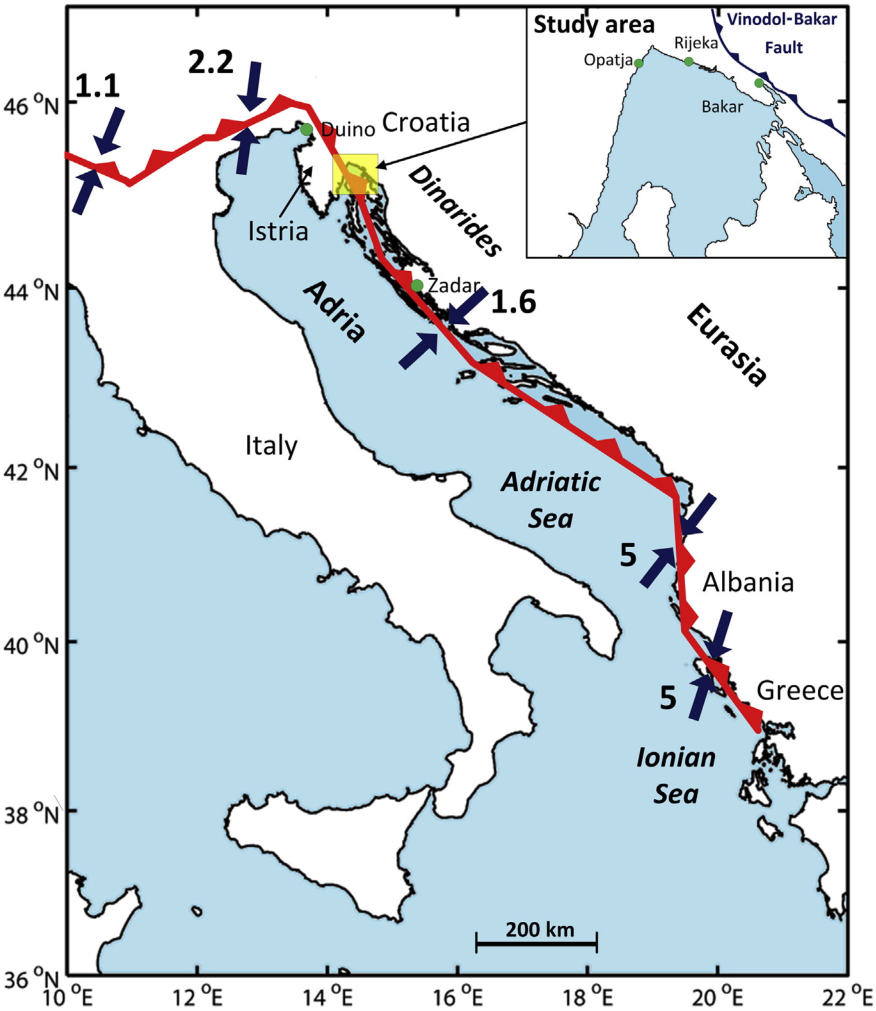

Fig. 1. Location map showing the approximate plate boundaries between Eurasia and Adria (roughly corresponding to the Adriatic Sea) and the rates of contraction (mm/yr) derived from GPS. Based on [10]. In the inset, the Rijeka-Bakar area and the Vinodol-Bakar Thrust (VBT).

dislocation theory (e.g. [20]). Fault parameters can be determined from a numerical solution (inversion) of a system of redundant equations connecting ground deformation (in this case of coastal subsidence) with the fault parameters; these equations are known as Okada equations [8,16,20]. In order to avoid any bias in the modeling, all parameters of this fault were assumed unknown ("free"), for example the fault depth or strike were not assumed a priori known and were left to vary within wide, reasonable ranges; simply unreasonable values were excluded [8].

The output of this analysis was that observed tectonic dislocations (additional, gradual drowning of already submerged coastal notches in the historical times) can be explained by activity of a 26-km long, shallow, NE-dipping thrust (dip 48°, strike N48°W), reaching from the depth of approximately 6.5 km to the surface. A seismic moment $Mo = 1.6 \times 10^{26}$ dyne cm was calculated. Using the typical formulas

$$M = 0.66 \log_{10}(Mo) - 10.7 \tag{1}$$

$$Mo = \mu A s \tag{2}$$

where Mo is seismic moment, M the earthquake magnitude, A the area of the activated rectangular fault surface, length times width, s the fault slip, μ, a constant, this corresponds to a magnitude $M = 6.8$ earthquake. Details on data and methodology, as well as alternative fault models were presented in [16].

Because of limitations of data (coastal data only), there is some uncertainty in estimated fault parameters. Still, the pattern of subsidence indicates clearly that the fault can only be close or slightly NE of the Bakar Bay, but clearly, there is a trade-off between fault length, width and slip (the three parameters which define Mo; Eq (2)), so that a longer fault cannot be excluded. In the compressional margin of NW Croatia, the pattern and the recorded amplitude of ground subsidence (up to 60 cm; Fig. 4) can be related with a major thrust only. Although no a priori constraints in the fault modeling were introduced, the surface trace of the modeled thrust correlates excellently with the Vinodol-Bakar Thrust (Fig. 4), which is in fact the only major thrust in the area. This obviously indicates its reactivation [16,21]. However, no significant surface faulting was expected, because of the composite structure of this thrust (better fault zone) and because faulting in the uppermost strata is expected to be accommodated by internal deformation of soft sediments in the Vinodol-Bakar Thrust. Only high seismic intensities are expected along the upper edge of the thrust, and this is consistent with the linear intensities estimated by Herak et al. [18]. Furthermore, the distribution of high seismic intensities of the 1750 earthquake (Fig. 4) are likely to indicate that the

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reactivation of the Vinodol-Bakar Thrust, responsible for the differential subsidence of coastal notches is dated to 1750.

In other words, there is evidence of a triple clear correlation between three independent features/effects: (1) the Vinodol-Bakar Thrust derived on the grounds of geologic mapping, (2) the finite fault derived from modeling of coastal data and (3) the distribution of the intensities of the 1750 earthquake derived from historical and archaeological data. Such a triple correlation can only indicate a causative relationship between reactivation of the Vinodol-Bakar Thrust, the differential drowning of notches (i.e. below the level of quasi-regional subsidence of 55 cm) and seismic accelerations during the 1750 and previous earthquakes [21].

Still, the question arising is whether the differential notch subsidence occurred during a single earthquake in 1750, or represents the cumulative effect of the 1750 and of certain previous or later earthquakes, especially some of those documented by Herak et al. [18]. In the first case (one single earthquake), the computed seismic moment can be explained by an earthquake with $M6.8$ (see above). In the second case, which represents our preferred scenario, the observed differential notch subsidence is associated with repeated reactivations of the Vinodol-Bakar Thrust, with cumulative seismic moment equal to that estimated from the inversion and eq. (1), of the order of 10^{26} dyne cm. Still, such smaller earthquakes cannot be of an order of magnitude of 5, because their corresponding seismic moment is about 1000 smaller, and about 1000 earthquakes would be necessary to explain the computed seismic moment. Hence the observed subsidence was associated with one or more $M > 6.0$ earthquakes. .

5. Discussion

In the past, seismological information for the Bakar-Rijeka area was poor, but new clear historical and archaeological evidence presented permits to recognize that the 1750 earthquake was associated with high (>VII) intensities along a quasi-linear zone more than 40 km long (Fig. 4).

A first scenario proposed by Herak et al. [18] is that observed intensities can be assigned to a small magnitude (~$M5.0$) earthquake and to amplification of accelerations in rather isolated karstic depressions filled with young sediments (i.e. soil dynamics effects). This scenario was generalized for all known earthquakes which occurred in the last 500 years in the wider Rijeka area, and for all these earthquakes a small magnitude (~$M5.0$) was assigned (Fig. 3).

A first difficulty with this interpretation is that slip and seismic moment associated with such small earthquakes are small, and hence they cannot explain the inferred relatively high convergence between Eurasia and Adria, ~2 cm/yr (Fig. 1). This rate corresponds to convergence of 10 m for the last 500 years, and this would signify that this active convergence front was essentially aseismic. A second difficulty is that areas with intensities ≥ VII are distributed along a narrow quasi-linear zone about 40 km long which correlates with the Vinodol-Bakar Thrust (Fig. 4). The length of this zone indicates release of seismic energy much higher than that justified by ~ M 5.0 earthquakes, even if directivity effects are taken into consideration [22]. A third difficulty is that there has not been

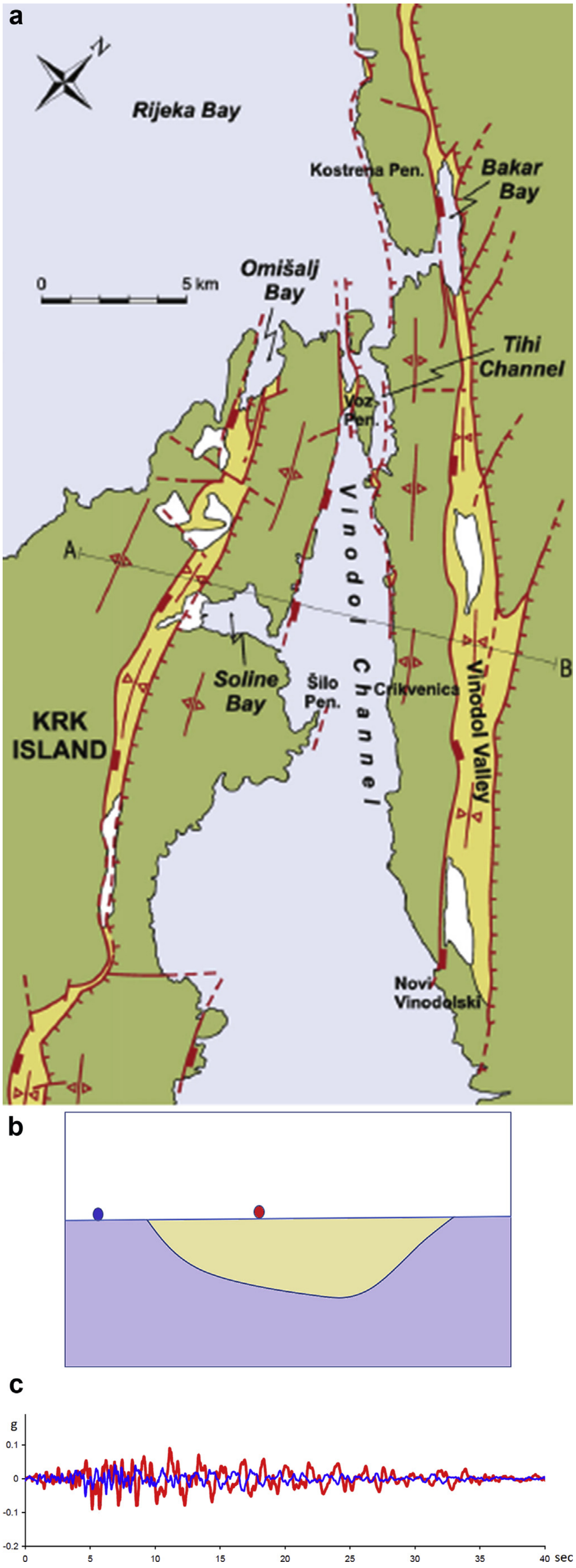

Fig. 2. a: The Vinodol-Bakar Thrust (VBT) is a long and narrow graben, a composite thrust system which represents the main fault in the area, and for this reason it is expected to be associated with major earthquakes. Modified after Benac et al. [17]. For location see frame marked 2 in Fig. 3. b, c: Conceptual model to explain the amplification of seismic accelerations and intensities on top of a valley sediments (or a graben such as that in (a)), relative to those in the nearby rocks. Red and blue dots and graphs indicate the location and the time histories of acceleration (normalized values), indicative of local amplification effects. (c) is based on accelerometer records of the 2017 Mexico earthquake (based on unpublished data of G. Gazetas and E. Garini).

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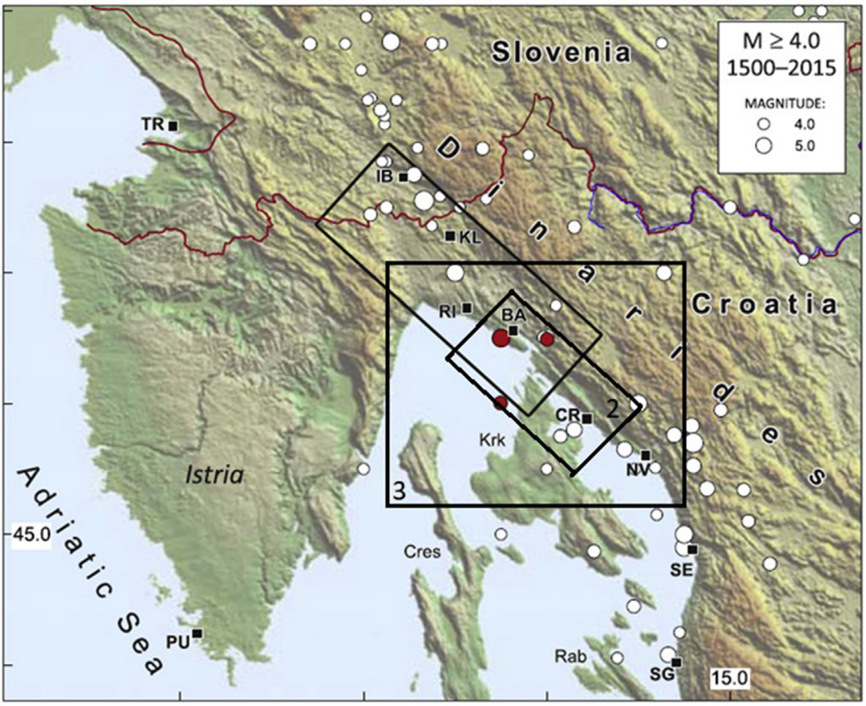

Fig. 3. Seismicity in the Rijeka (FI) and Bakar (BA) area during the last five centuries, according to Herak et al. (2017) [21]. The epicenter of the 1750 earthquake, derived from macroseismic data, is marked by a red circle next to Bakar (BA). A maximum earthquake magnitude 5 is inferred, but this result is questioned.

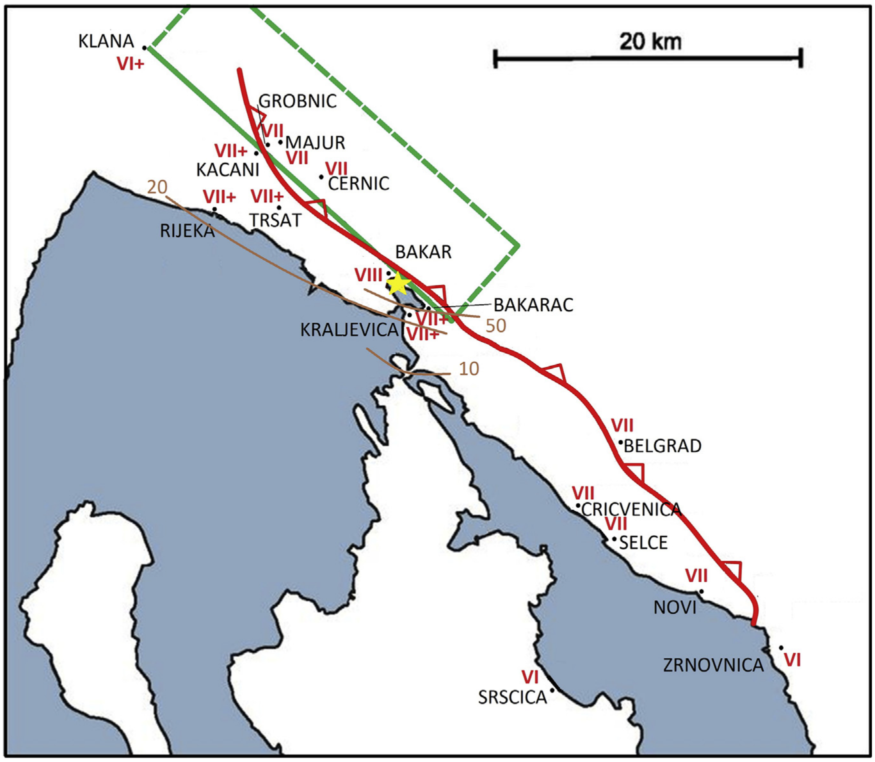

Fig. 4. Correlation between (1) the intensities of 1750 earthquake (red Latin numbers), (2) the trace of the Vinodol-Bakar Thrust (VBT; red curve, with ticks on the hanging wall), and (3) the horizontal projection of the finite model of the fault responsible for differential subsidence of coastal notches in the wider Rijeka-Bakar area (green rectangular; surface trace indicated by a continuous line). Yellow star indicates the macroseismic epicenter of the 1750 earthquake. Brown curves represent selected contours of coastal tectonic subsidence (in cm), drawn from data on which was based the proposed finite fault model. Based on data from Ref. [12,16–18]. Location map in Figs. 1 and 3.

presented clear evidence that the areas of high intensities, especially for towns more distant from the epicenter, are indeed located in isolated karstic depressions, in which amplification of seismic intensities are expected (Fig. 2b and c). On the contrary, certain of these sites, for example ancient Rijeka, are located on hills.

The alternative scenario discussed above regards the 1750 earthquake as a strong ($\geq M6.0$) event, associated with the Vinodol-Bakar Thrust. However, because local amplification of seismic intensities are expected because of soil dynamics effects, we may conclude that the primary fault rupture produced relatively low source accelerations. This may be a systematic characteristic of the earthquakes in the area explain why some of them were probably ignored or underestimated. Hence a modern parallel for the Rijeka-Bakar earthquakes is the 2014, *M*6.9 Northern Aegean strong earthquake, which produced moderate accelerations and intensities [8].

The association of the Vinodol-Bakar Thrust with the 1750 seismic fault is justified by the large scale of the observed ground deformation (20 cm subsidence along a distance of >20 km; Fig. 4) for a very specific reason: Large scale ground deformations can be generated only by large earthquakes, large earthquakes can be generated by major faults only, and the only candidate fault in the study area is the Vinodol-Bakar Thrust system (Fig. 2).

6. Soil dynamic effects in ancient earthquakes

Amplification or attenuation of seismic accelerations, leading to higher or lower seismic intensities and hence to destruction, landslides, etc., is a critical problem for modern earthquakes, but a problem rarely only addressed in palaeoseismic events, mainly for lack of the necessary evidence. One of the few known exceptions is a seismic sequence which produced major destruction in Crete, Cyprus, Sicily and Northern Africa in AD365. These destructions were assigned to a number of different earthquakes and not a single earthquake from Crete. The reason is that the destruction of low-height (one to two-story, and hence of high-frequency) structures in Cyprus, about 500 km from Crete, require high-period seismic waves which are fully attenuated at distances of about 100 km from the source (epicenter). On the contrary, long-period seismic waves can be radiated from the source and preserve much energy along distances of >500 km, but ordinary structures are not sensitive (resonant) to such waves [23], as has been demonstrated in the case of the 1985 Mexico earthquake [9].

The 1750 Croatia earthquake is hence a rather unique case, which permits to examine in details the role of soil dynamic effects in ancient earthquakes, and to select between two different scenarios for the magnitude of this earthquake. The study of this earthquake, in combination with high and slow seismic acceleration events noticed in the Introduction, indicate that the recorded signs of ancient earthquakes in terms of seismic intensities reflect a convolution of three effects: (1) of the fault dimensions broadly described by the seismic moment (eq. (1)) and the earthquake magnitude. (2) of the fault rupture dynamics, reflected in high or low accelerations, which are commonly described by the PGA (Percentage of Gravity Acceleration), and which is not proportional to the earthquake magnitude. For example, there have been recorded moderate to large (~*M*6) earthquakes with very high (PGA >0.50 g) accelerations and intensities [24,25], large earthquakes (*M*6.9) with moderate accelerations near the fault [8], even silent earthquakes, with extremely slow strain release [26], not felt nor recorded by accelerometers. And (3) of local soil dynamics effects, producing attenuation or amplification of seismic accelerations and intensities due to the topography, the local lithological conditions and the directivity of seismic waves (Fig. 2; [6,22]). The inverse approach, estimation of the three effects from the available historical, geological etc. data seems a challenge, but certainly a need for successful estimation of the seismic risk.

7. Conclusions

The 1750 Croatia earthquake was associated with high (VII-VIII) intensities along a distance of >40 km (Fig. 4), and their interpretation is a matter of debate, because soil dynamics effects are taken into consideration.

A first scenario suggests that observed high intensities during this and other historical earthquakes indicate local amplification of seismic accelerations/intensities in small karstic valleys (see Fig. 2) and low magnitude seismic events (~*M*5.0) in the last 500 years; this points to an unusual, essentially aseismic plate collision front in Northern Adriatic.

An alternative, preferred scenario is that although local amplification effects are definitely expected, the observed high (VII-VIII) intensities along a distance of >40 km (Fig. 4) cannot be explained by a moderate magnitude earthquake, even if directivity effects are taken into consideration. This result is consistent with finite fault modeling of the 1750 earthquake on the basis of elastic dislocation analysis of differential submersion of coastal notches. Model fault correlates with the Vinodol-Bakar Thrust, the major tectonic structure in the area, perhaps the only one which can generate major earthquakes, and the distribution of the intensities of the 1750 event. This triple correlation of independent lines of evidence permits to define the characteristics/parameters of the 1750 Croatia earthquake, a $M > 6$ magnitude event which produced normal to moderate seismic intensities.

The overall results and conclusions of this study are expected to be important for the reliable estimation of the seismic risk and hazard in Croatia; they also indicate that the collision front in N Adriatic is not essentially aseismic.

This study highlights also the need to combine both the seismological/geological/geophysical and the engineering (soil dynamics) characteristics of ancient earthquakes. This is because certain parameters of ancient earthquakes are usually inferred from seismic intensities which are derived from fragmentary historical or archaeological evidence in one or a few sites only [1,2].

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References

[1] N. Ambraseys, Value of historical records of Earthquakes, Nature 232 (1971) 375–379, https://doi.org/10.1038/232375a.
[2] E. Guidoboni, A. Comastri, G. Traina, Catalogue of Ancient Earthquakes in the Mediterranean Area up to 10th Century, Istituto Nazionale di Geofisica, Roma, 1994, p. 504.
[3] R. Yeats, C.S. Prentice, Introduction to special section: paleoseismology, J. Geophys. Res. 101 (B3) (1996) 5847–5853, https://doi.org/10.1029/95JB03134.
[4] S. Stiros, Unexpected shock rocks an “aseismic” area, Eos Trans. AGU 76 (50) (1995) 513–519, https://doi.org/10.1029/95EO00316.
[5] D. Assimaki, G. Gazetas, E. Kausel, Effects of local soil conditions on the topographic aggravation of seismic motion: parametric investigation and recorded field evidence from the 1999 Athens earthquake, Bull. Seismol. Soc. Am. 95 (3) (2005) 1059–1089.
[6] D. Assimaki, S. Jeong, Groundmotion observations at Hotel Montana during the M7.0 2010 Haiti earthquake: topography or soil amplification? Bull. Seismol. Soc. Am. 103 (5) (2013) 2577–2590.
[7] C. Del Gaudio, M. Di Domenico, P. Ricci, G. Verderame, Preliminary prediction of damage to residential buildings following the 21st August 2017 Ischia earthquake, Bulletin of Earthquake Engineering (2018), https://doi.org/10.1007/s10518-018-0368-y in press.
[8] V. Saltogianni, M. Gianniou, T. Taymaz, S. Yolsal-Çevikbilen, S. Stiros, Fault-slip source models for the 2014 Mw 6.9 Samothraki-Gökçeada earthquake (North Aegean Trough) combining geodetic and seismological observations,

J. Geophys. Res. (Solid Earth) 120 (12) (2015), https://doi.org/10.1002/2015JB012052.

[9] B.A. Bolt, The nature of earthquake ground motion, in: F. Naeim (Ed.), The Seismic Design Handbook, Springer, 2001, https://doi.org/10.1007/978-1-4615-1693-4_1.

[10] E. Serpelloni, M. Anzidei, P. Baldi, G. Casula, A. Galvani, Crustal velocity and strain-rate fields in Italy and surrounding regions: new results from the analysis of permanent and non-permanent GPS networks, Geophys. J. Int. 161 (3) (2005) 861–880.

[11] S. Pondrelli, S. Salimbeni, A. G. Ekström, Morelli, P. Gasperini, G. Vannucci, The Italian CMT dataset from 1977 to the present, Phys. Earth Planet. Inter. 159 (3–4) (2006) 286–303.

[12] C.. Benac, M. Juracic, I. Blaskovic, Tidal notches in zinodol channel and bakar bay, NE Adriatic Sea: indicators of recent tectonics, Mar. Geol. 248 (2008) 151–160.

[13] S. Faivre, E. Fouache, M. Ghilardi, F. Antonioli, S. Furlani, V. Kovačić, Relative sea level change in western Istria (Croatia) during the last millennium, in: Quaternary International vol. 232, 2011, pp. 132–143, https://doi.org/10.1016/j.quaint.2010.05.027.

[14] D.H. Natawidjaja, K. Sieh, J. Galetzka, et al., Interseismic deformation above the sunda megathrust recorded in coral microatolls of the Mentawai Islands, West Sumatra, J. Geophys. Res. B Solid Earth 112 (2) (2007) art. no. B02404.

[15] M. Shishikura, T. Echigo, Y. Namegaya, Evidence for coseismic and aseismic uplift in the last 1000 years in the focal area of a shallow thrust earthquake on the Noto Peninsula, west-central Japan, Geophys. Res. Lett. 36 (2) (2009) art. no. L02307.

[16] S. Stiros, F. Moschas, Submerged notches, coastal changes and tectonics in the Rijeka area, NW Croatia. Mar. Geol. 329–331 (2012) 103–112.

[17] C. Benac, M. Juracic, T. Bakran-Petricioli, Submerged tidal notches in the Rijeka Bay NE Adriatic Sea: indicators of relative sea-level change and of recent tectonic movements, Mar. Geol. 212 (2004) 21–33.

[18] D. Herak, I. Sović, I. Cecić, M. Živčić, I. Dasović, M. Herak Historical, Seismologist: Historical seismicity of the Rijeka region (Northwest External Dinarides, Croatia)—Part I: Earthquakes of 1750, 1838, and 1904 in the Bakar epicentral area, Seismol. Res. Lett. 88 (3) (2017), https://doi.org/10.1785/0220170014.

[19] N. Takai, M. Shigefuji, S. Rajaure, S. Bijukchhen, M. Ichiyanagi, M, Raj Dhital, S. Sasatani, Strong ground motion in the Kathmandu Valley during the 2015 Gorkha, Nepal, earthquake, Earth Planets Space 68 (2016) 10, https://doi.org/10.1186/s40623-016-0383-7.

[20] Y. Okada, Surface deformation due to shear and tensile faults in a half space, Bull. Seismol. Soc. Am. 75 (4) (1985) 1135–1154.

[21] S. Stiros, Comment on “Historical Seismicity of the Rijeka Region (Northwest External Dinarides, Croatia)—Part I: Earthquakes of 1750, 1838, and 1904 in the Bakar Epicentral Area” by Herak et al, Seismol. Res. Lett. 88 (6) (2017) 1534–1536. https://doi.org/10.1785/0220170098.

[22] I. Beresnev, G. Atkinson, FINSIM—a FORTRAN program for simulating stochastic acceleration time histories from finite faults, Seismol. Res. Lett. 69 (1998) 27–32, https://doi.org/10.1785/gssrl.69.1.27.

[23] S. Stiros, The 8.5+ magnitude, AD365 earthquake in Crete: coastal uplift, topography changes, archaeological and historical signature, Quat. Int. 216 (2010) 54–63.

[24] B. Bradley, M. Quigley, R.J. Van Dissen, N.J. Litchfield, Ground motion and seismic source aspects of the Canterbury earthquake sequence, Earthq. Spectra 30 (1) (2014) 1–15, https://doi.org/10.1193/030113EQS060M.

[25] N. Theodoulidis, C. Karakostas, V. Lekidis, K. Makra, B. Margaris, K. Morfidis, C. Papaioannou, M. Rovithis, T. Salonikios, A. Savvaidis, The Cephalonia, Greece, January 26 (M6.1) and February 3, 2014 (M6.0) earthquakes: near-fault ground motion and effects on soil and structures, Bull. Earthq. Eng. 14 (2015) 1–38, https://doi.org/10.1007/s10518-015-9807-1.

[26] Y. Jiang, S. Wdowinski, T.H. Dixon, M. Hackl, M. Protti, V. Gonzalez, Slow slip events in Costa Rica detected by continuous GPS observations, 2002-2011, Geochem. Geophys. Geosyst. 13 (2012), https://doi.org/10.1029/2012GC004058. Q04006.

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