



# Neo-deterministic seismic hazard assessment of Corsica-Sardinia block

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## Abstract

The Corsica-Sardinia lithospheric block is commonly considered as a region of very low seismicity and the scarce reported seismicity for the area has till now precluded the reliable assessment of its seismic hazard. The time-honored assumption has been recently questioned and the historical seismicity of Sardinia has been reevaluated. Even more, several seismogenic nodes capable of  $M5+$  have been recognized in the Corsica-Sardinia block exploiting the morphostructural zonation technique, calibrated to earlier results obtained for the Iberian peninsula, which has structural lithospheric affinities with the Corsica-Sardinia block. All this allows now for the computation of reliable earthquake hazard maps at bedrock conditions exploiting the power of Neo Deterministic Seismic Hazard Assessment (NDSHA) evaluation. NDSHA relies upon the fundamental physics of wave generation and propagation in complex geologic structures and generates realistic time series from which several earthquake ground motion parameters can be readily extracted. NDSHA exploits in an optimized way all the available knowledge about lithospheric mechanical parameters, seismic history, seismogenic zones and nodes. In accordance with continuum mechanics, the tensor nature of earthquake ground motion is preserved computing realistic signals using structural models obtained by tomographic inversion and earthquake source information readily available in literature. The way to this approach has been open by studies focused on continental Italy and Sicily, where the agreement between hazard maps obtained using seismogenic zones, informed by earthquake catalog data, and the maps obtained using only seismogenic nodes are very good.

**Keywords** Corsica-Sardinia block · Seismic hazard · NDSHA · MSZ

## 1 Introduction

In contrast to the neighboring Apennine Peninsula, the seismic history of the Corsica-Sardinia region, reported by earthquake catalogs, is characterized by sporadic and weak shocks, magnitudes of which, as a rule, do not exceed 5 (Rovida et al. 2020, 2021; Postpischl 1985). Meletti et al (2021) concluded that Sardinia island is “not earthquake-less” and contradict the time-honored assumption. The recent instrumental observations evidence the ongoing low seismic activity in the region: specifically, during 2020 the INGV seismic network recorded four small shocks in Sardinia (<http://terremoti.ingv.it>). The very scarce seismicity reported in official documents (parametric catalogs and historical records, Table 2) prevented till now a reliable assessment of earthquake hazard of the single Sardinia-Corsica lithospheric block, characterized by a common geodynamic evolution (Minzoni 1991). In a recent paper Gorshkov et al. (2021) evaluated the seismic potential of the region employing the morphostructural zoning (MSZ) that allows

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for the identification of the location of potential earthquakes independently from the seismic history just relying on the systematic and quantitative analysis of the available geological and morphostructural data. The MSZ delineates the hierarchical system of morphostructural blocks, the network of lineaments bounding the blocks, and the loci of nodes formed around intersections of lineaments. Nodes are treated as earthquake controlling structures (Gorshkov et al. 2003). Their seismic potential is evaluated exploiting the existing criteria of seismicity defined earlier for seismogenic ( $M5+$ ) nodes in Iberia, whose structural setting is grossly similar to the one of the Corsica-Sardinia block (Raykova and Panza 2010; Panza et al. 2007; Carminati et al. 2012). 24 out of the 81 nodes delineated by MSZ meet the characteristic features (criteria of seismicity) of the seismogenic nodes prone to  $M5+$  that have been defined by pattern recognition in the Iberian Peninsula (Gorshkov et al. 2010). The study by Gorshkov et al. (2021) suggests that the seismic potential of the Corsica-Sardinia block is not low and provides the key information for long-term reliable seismic hazard assessment of the region and motivates the application of the Neo Deterministic Seismic Hazard Assessment (NDSHA) to reliably evaluate the earthquake hazard of the study area.

## 2 Methodology and data

NDSHA (Panza et al. 2001a, b, 2012; Panza and Bela 2020; Bela and Panza 2021; Panza et al. 2021) is a now well established technique based on the physical description of the earthquake rupture process and of the seismic propagation paths aimed to obtain synthetic seismograms from which reliable ground motion parameters relevant to engineering applications can be extracted even when the available records are very poor. NDSHA exploits all the known seismicity and other potential seismic sources and the available knowledge of the Earth structure (i.e. the propagation medium, the ray-path), preserving the tensor nature of earthquake ground motion (Aki and Richards 2002). While ground motion parameters at the regional scale are given, as a rule, for bedrock conditions, more detailed studies can be performed at specific sites, taking into account the nature of local soil and the rupture complexity at the source. We refer the reader to previous works for a detailed description of the theoretical and computational workflow of NDSHA (e.g. Panza et al. 2001a, b, 2012; Panza and Bela 2020; Bela and Panza 2021; Panza et al. 2021), while in the following we describe the input data and the procedural steps applied in this study.

No seismogenic zones (Meletti et al. 2008) have been defined for the study area, thus we use only the seismogenic nodes identified by MSZ as seismic sources (Fig. 1), such approach being proven valid by Rugarli et al. (2019)

for continental Italy and Sicily. The nodes are prone to  $M5+$  earthquakes (Gorshkov et al. 2021), thus we assign  $M_W=5$  to all sources that are uniformly distributed within the nodes of 25 km of radius (Fig. 2), at a fixed depth of 10 km.

Very little information about the focal mechanisms of earthquake sources in the study area is available and the few mechanisms that have been determined mostly fall outside the nodes. Therefore, we associate to each node a representative average focal mechanism determined by Pondrelli et al. (2020) for the Sardinia-Corsica Block. Of this mechanism we retain dip and rake angles, while the strike is chosen according to the orientation of the higher rank lineament intercepted by each node (Fig. 2). Anyway, using the average strike for all the nodes brings typically consistent results, so the latter will not be presented in the following section.

The regional structure that is used as propagation medium is described by a set of 1D an elastic seismic cellular models (Fig. 3 and Table 2) with a resolution of  $1^\circ \times 1^\circ$  (Brandmayr et al. 2010; Brandmayr 2012) obtained from surface wave tomography down to 350 of depth, while a standard reference structure (Kennett and Engdahl 1991) was used at larger depths.

Regional hazard maps are computed using the Size Scaled Point Source model (SSPS, after Parvez et al. 2011) approximation. The Design Ground Acceleration (DGA) is obtained considering appropriate response spectra (Panza et al. 2001a, b), specifically the Eurocode 8 (CEN 2004) response spectrum for soil type A.

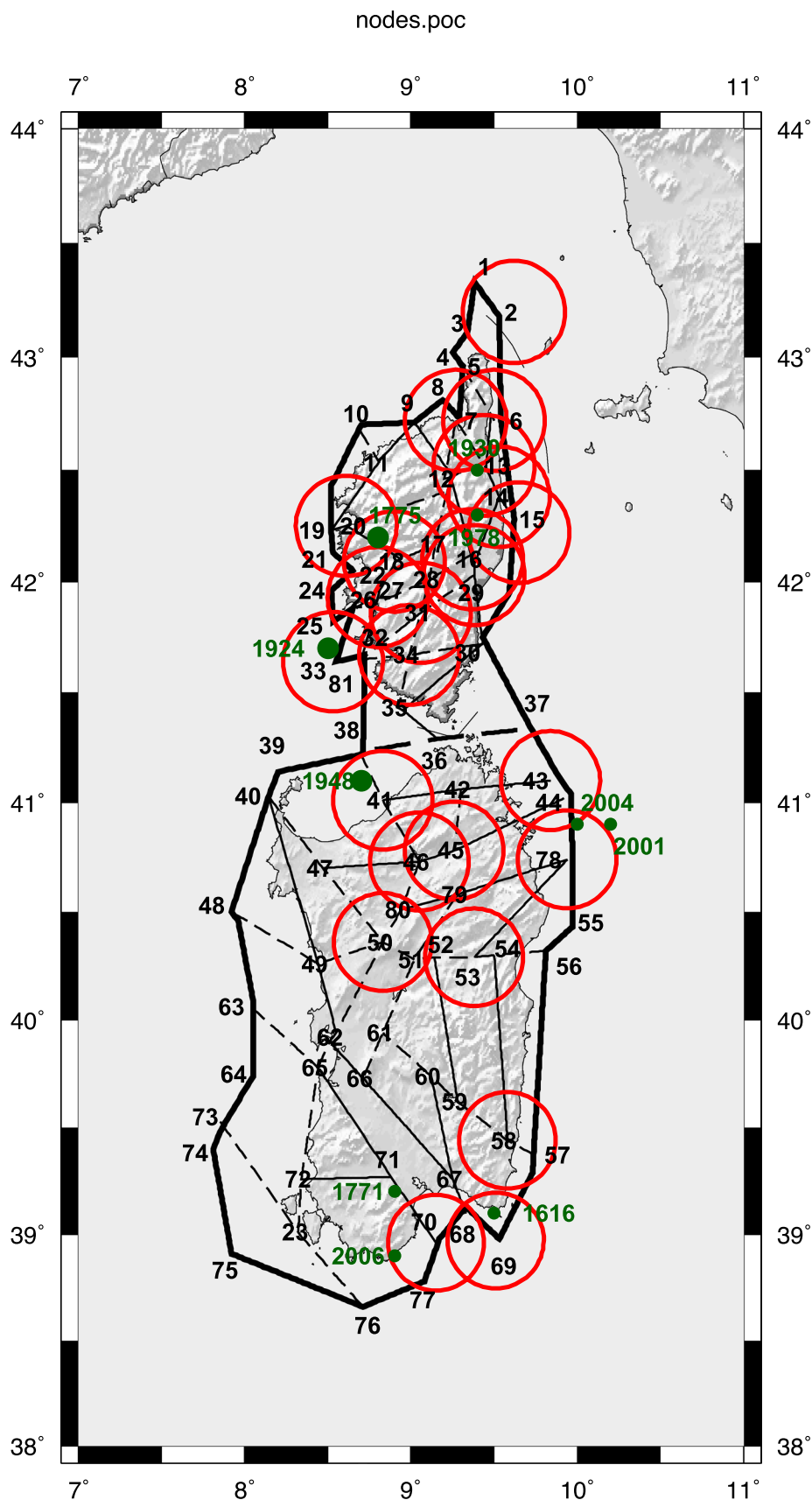
## 3 Results and discussion

Vertical displacement map show widespread low values on both Corsica and Sardinia ( $<0.1$  cm). Similarly, vertical velocities are everywhere  $<0.5$  cm/s and vertical DGAs are  $<0.005$  g (Fig. 4, top). Horizontal components are slightly higher: horizontal displacement tops 0.5 cm in most of Corsica and eastern Sardinia; horizontal velocities reach 1 cm/s on the western coast of Corsica and the Cagliari area; horizontal DGAs reach 0.01 g in Corsica and eastern Sardinia (Fig. 4, bottom).

These values are consistent with  $I=V$  (MCS, applying the regression after Panza et al. (2001a, b) reported for most of the historical events felt in the area (Meletti et al. 2021). However, Meletti et al. (2021) also report  $I=VI$  caused by the 1948–1949 seismic sequence with epicentral area in NW Sardinia.

$M_W=5$  is the lower bound of the magnitude threshold identified by the pattern recognition methodology. Thus, following Rugarli et al. (2019), in a second run we increase the source magnitude to  $M_W=5.5$ , applying an increment defined as  $\Delta M = \gamma_{EM} \sigma_M$ , where  $\gamma_{EM}$  (here set to 2.0) is a

**Fig. 1** Map of the study area with morphostructural zonation after Gorshkov et al. (2021). Thick lines are the lineaments of the first rank, medium lines are the lineaments of the second rank, thin lines are the lineaments of the third rank; continuous lines represent the longitudinal lineaments; dashed ones represent the transverse lineaments. Seismogenic nodes prone to  $M \geq 5$  earthquakes are marked by red circles. Green large dots denote epicenters of earthquakes with  $M \geq 5.0$ , while green small dots depict epicenters of earthquakes with  $4.0 \leq M < 5.0$ , after CPTI15 catalog (<https://emidius.mi.ingv.it/CPTI15-DBMI15>). For seismic events details see Table 1. Color figure online



**Table 1** Earthquakes M4+ in the Corsica-Sardinia region after the CPTI15 (after Gorshkov et al. 2021). Events with  $M \geq 5$  are marked in bold

Date	Lat	Long	M	<i>I</i>	CPTI15 ID
1616 06 04	39.1 N	9.5E	Mw4.9		Sardegna merid
1771 08 17	39.2 N	8.9E	Mw 4.4	V	Sardegna merid
<b>1775 10 22</b>	42.2 N	8.8E	<b>Mw5.1</b>		Vico (Corsica)
<b>1924 01 24</b>	41.7 N	8.5E	<b>Mw5.0</b>		Sardegna nord-occ
1930 02 08	42.5 N	9.4E	Mw 4.5		Castagniccia
<b>1948 11 13</b>	41.1 N	8.7E	<b>Mw5.1</b>	V–VI	Mar di Sardegna
1978 04 03	42.3 N	9.4E	Mw 4.5		Corsica
2001 03 03	40.9 N	10.0E	Mw4.1		Tirreno centrale (MARE)
2004 12 18	40.9 N	10.2E	ML4.3		Tirreno centrale (MARE)
2006 03 24	38.9 N	8.9E	Mw4.0		Capo Teulada

When available, maximum felt intensity (*I*) has been added from Meletti et al. (2021)

tunable safety factor, variable from 1.5 to 2.5 (Rugarli et al 2019), and  $\sigma_M$  (here set to 0.25) is a value representative of the global uncertainty on magnitude determination 0.2–0.3 (Báth 1973). We refer to the incremented magnitude value as  $M_{\text{design}}$ .

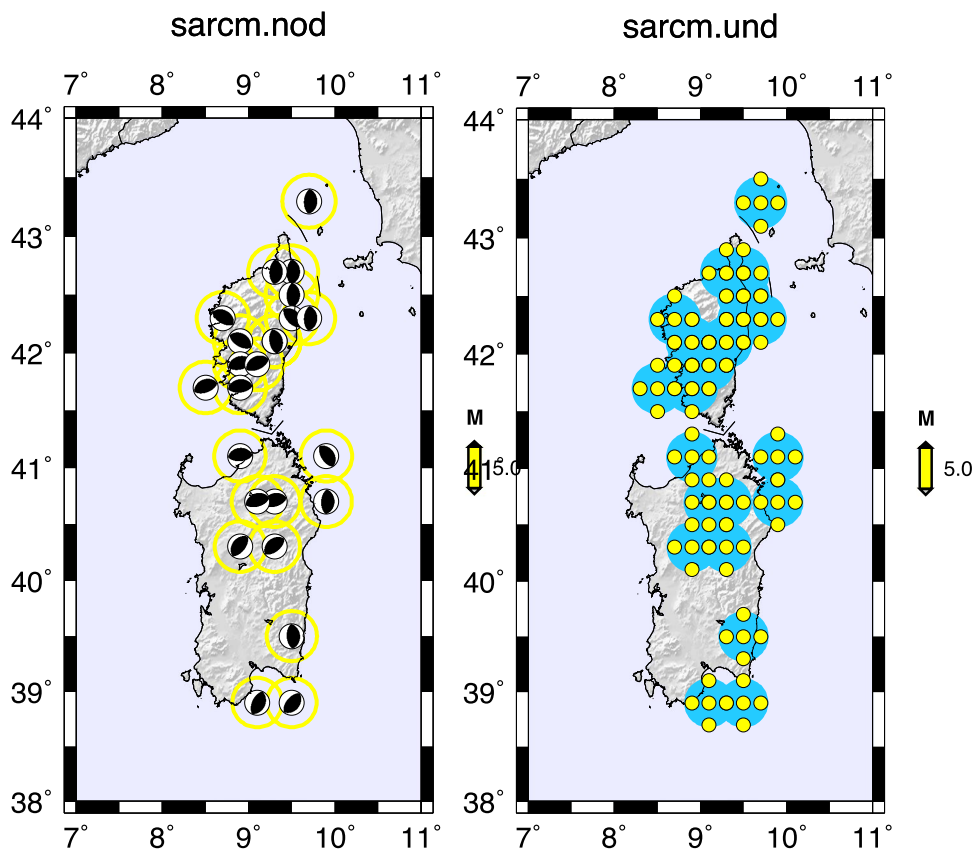
Maps obtained in such a way (second run) show vertical displacement up to 0.5 cm in the whole study area, vertical velocities up to 1 cm/s in most of Corsica and interior of Sardinia and vertical DGAs up to 0.02 g in SW Corsica and, locally, in western Sardinia (Fig. 5, top).

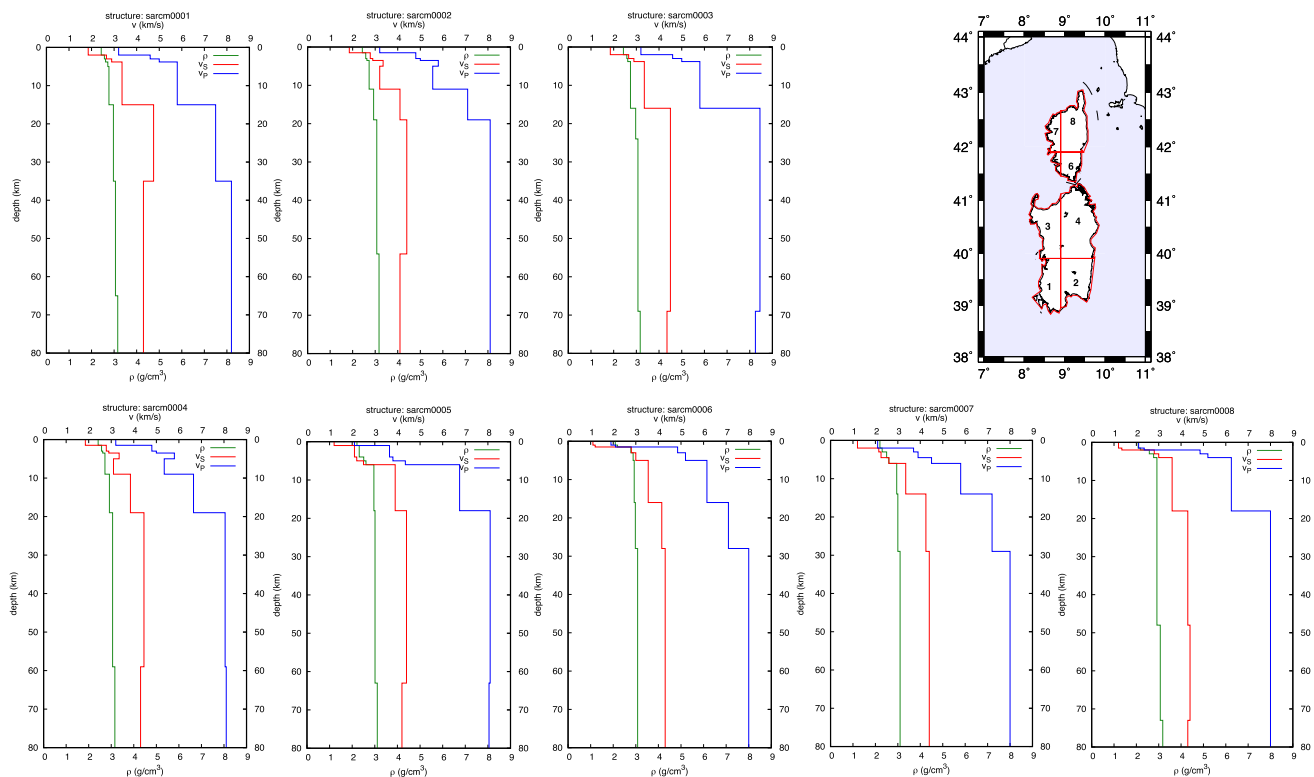
Horizontal displacement reaches 2 cm in central-western Corsica; horizontal velocities reach 4 cm/s in W Corsica and Cagliari area, while are generally over 1 cm/s in most of the study area; horizontal DGAs can be as high as 0.04 g in most of the study area excepted W coast of Sardinia (Fig. 5, bottom). These values correspond to  $I = VII$  on the MCS scale (Panza et al. 2001a, b).

In our opinion, the second run supplies a reliable and conservative description of the actual seismic hazard of Corsica-Sardinia block, also on account of the scarce empirical knowledge of the seismicity of the area, including major uncertainties on the focal depth and mechanisms of the earthquakes.

Rugarli et al (2019) applied  $M_{\text{design}}$  to the rest of the Italian territory considering only seismogenic nodes and obtained hazard maps in agreement with those based on seismogenic zones and the CPTI04 catalog. Brandmayr et al. (2021) showed that the application of  $M_{\text{design}}$  (at 1 Hz cut-off frequency) in Kosovo gives hazard levels consistent with 10 Hz cut-off frequency computation, which needs

**Fig. 2** Map of the seismogenic nodes with associated magnitude, representative focal mechanism (left) and location of the sources within the nodes (right)





**Fig. 3** Structural cellular models of the study area (after Brandmayr 2012) down to 80 km of depth. Models are coded with progressive numbers as shown in the inset map.  $\rho$  is density (color figure online). For details of structural models down to 350 km, see Table 2

a knowledge of sources and structures with a detail not available for the study area.

Therefore, we consider the ground motion maps obtained applying  $M_{\text{design}}$  the most, now possible, reliable advancement in the understanding of the seismic hazard of the area.  $M_{\text{design}}$  is a readily available tool for assessing and mitigating seismic risk, especially where critical infrastructures (e.g. rad-waste surface disposal facility, natural-gas pipelines, etc.) may be planned.

## 4 Conclusions

NDSHA relies upon the fundamental physics of wave generation and propagation in complex geologic structures to generate realistic synthetic seismograms, used as input for the computation of several ground motion parameters, integrating all the available knowledge about seismic sources and medium structure. Seismogenic nodes identified in the Corsica-Sardinia block by Gorshkov et al. (2021) supply

information about the seismic potential of the study area filling the gap due to the scarce and poorly known seismic history of the area and allow for the assessment of seismic hazard using NDSHA.

Considering seismogenic nodes in Italy, Rugarli et al. (2019), showed that adding a safety increment  $\Delta M$  is equivalent to applying a partial safety factor  $\gamma_q$  to the seismic moment at the fault  $M_0$ , as normally asked by Eurocodes and other international standards for typical structural design. Ground motion estimates so obtained envelope the ones obtained using the seismic catalog. Similarly, we suggest that the application of seismogenic nodes and  $M_{\text{design}} = 5.5$  to Corsica-Sardinia block provides the most reliable assessment of seismic hazard of the area so far.

In particular, we show that large portions of Corsica and Sardinia could experience ground motion levels compatible with  $I = \text{VII}$  on the MCS macroseismic intensity scale. Such macroseismic intensity envelopes the values felt and documented so far, pointing out that some further actions of prevention and mitigation of seismic risk should be enforced, especially in the siting of critical infrastructures.

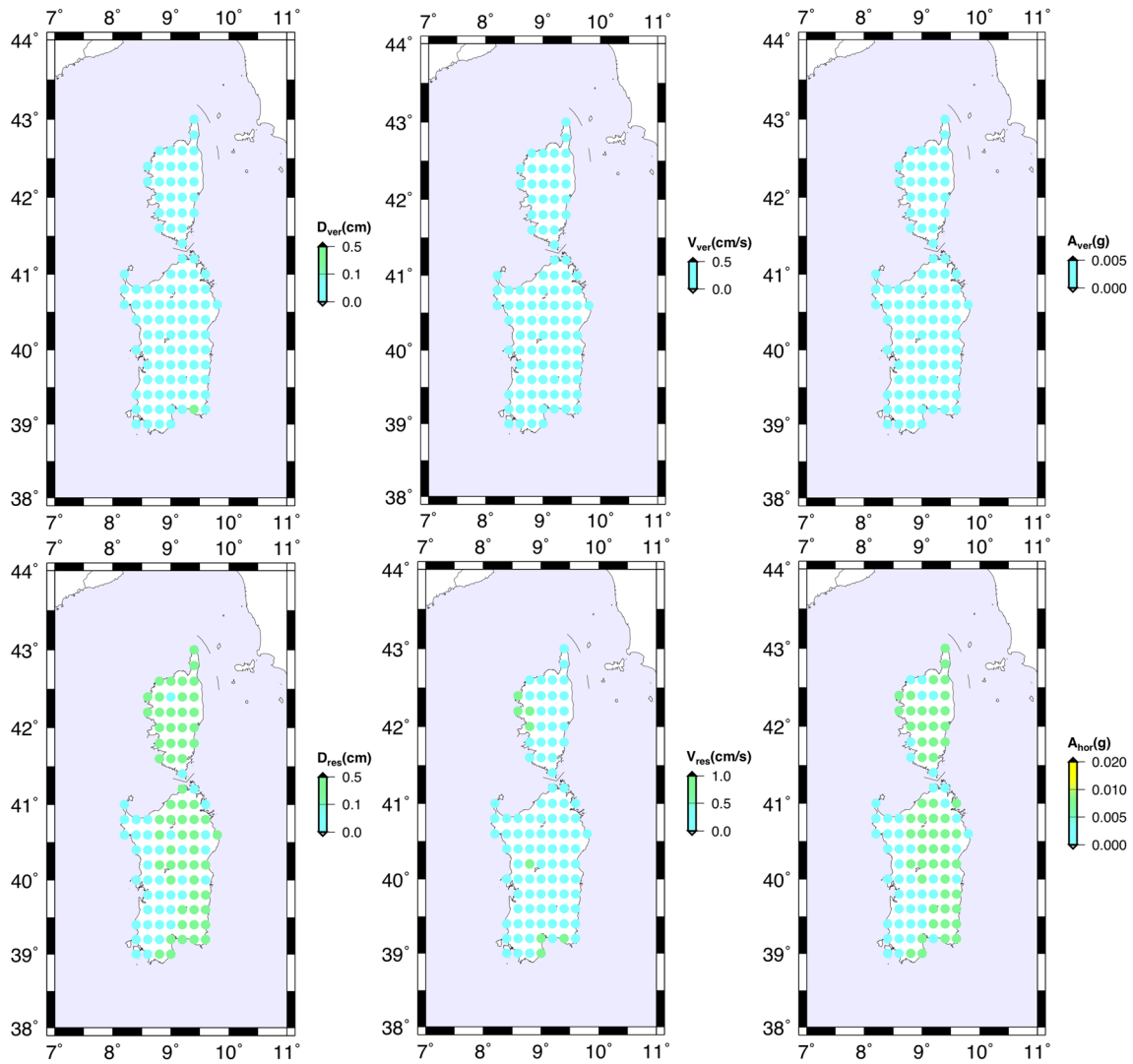
**Table 2** Structural models used in this study (after Brandmayr 2012) down to a depth of 350 km

Thk (km)	$\rho$ (g/cm <sup>3</sup> )	$V_p$ (km/s)	$V_s$ (km/s)	$Q_p$	$Q_s$	Z (km)
8.5° E 39.50° N—01						
2.00	2.43	3.20	1.85	638	290	2.00
1.00	2.57	4.60	2.66	638	290	3.00
0.80	2.62	5.00	2.89	616	280	3.80
1.20	2.72	5.80	3.35	616	280	5.00
10.00	2.77	5.80	3.35	506	230	15.00
20.00	2.97	7.50	4.75	286	130	35.00
30.00	3.06	8.20	4.30	176	80	65.00
95.00	3.16	8.20	4.30	176	80	160.00
110.00	3.28	8.20	4.30	220	100	270.00
80.00	3.50	8.85	4.75	330	150	350.00
9.5° E 39.5° N—02						
1.50	2.43	3.20	1.85	638	290	1.50
1.50	2.58	4.80	2.78	638	290	3.00
0.50	2.63	5.00	2.89	616	280	3.50
1.50	2.73	5.80	3.35	616	280	5.00
6.00	2.73	5.55	3.20	550	250	11.00
8.00	2.93	7.10	4.10	462	210	19.00
35.00	3.07	8.10	4.40	176	80	54.00
40.00	3.17	8.10	4.10	176	80	94.00
160.00	3.28	8.55	4.45	220	100	254.00
96.00	3.49	8.85	4.75	330	150	350.00
8.5° E 40.5° N—03						
2.00	2.43	3.20	1.85	638	290	2.00
1.00	2.58	4.60	2.66	638	290	3.00
0.80	2.62	5.00	2.89	616	280	3.80
12.20	2.74	5.80	3.35	484	220	16.00
8.00	2.97	8.45	4.50	396	180	24.00
45.00	3.07	8.45	4.50	176	80	69.00
90.00	3.17	8.25	4.35	176	80	159.00
110.00	3.28	8.50	4.50	220	100	269.00
81.00	3.50	8.75	4.75	330	150	350.00
9.5° E 40.5° N—04						
1.50	2.42	3.20	1.85	638	290	1.50
1.50	2.57	4.80	2.78	638	290	3.00
0.50	2.62	5.00	2.89	616	280	3.50
1.50	2.72	5.80	3.35	616	280	5.00
4.00	2.72	5.35	3.10	572	260	9.00
10.00	2.92	6.65	3.85	462	210	19.00
40.00	3.06	8.05	4.45	176	80	59.00
80.00	3.16	8.10	4.30	176	80	139.00
160.00	3.27	8.70	4.55	220	100	299.00
51.00	3.49	8.80	4.75	330	150	350.00
8.5° E 41.5° N—05						
1.00	2.21	2.10	1.20	572	260	1.00
3.00	2.31	3.65	2.10	572	260	4.00
1.00	2.51	3.80	2.20	550	250	5.00
1.00	2.61	4.35	2.50	550	250	6.00
12.00	2.96	6.75	3.90	418	190	18.00
45.00	3.01	8.10	4.40	176	80	63.00
50.00	3.11	8.05	4.20	176	80	113.00

**Table 2** (continued)

Thk (km)	$\rho$ (g/cm <sup>3</sup> )	$V_p$ (km/s)	$V_s$ (km/s)	$Q_p$	$Q_s$	Z (km)
45.00	3.20	8.10	4.40	176	80	158.00
105.00	3.30	8.40	4.45	440	200	263.00
87.00	3.52	8.70	4.75	330	150	350.00
9.5° E 41.5° N—06						
1.00	2.09	1.90	1.10	616	280	1.00
0.50	2.19	2.10	1.20	616	280	1.50
1.50	2.78	4.85	2.80	594	270	3.00
2.00	2.88	5.20	3.00	572	260	5.00
11.00	2.93	6.15	3.55	462	210	16.00
12.00	2.98	7.10	4.15	330	150	28.00
70.00	3.08	8.00	4.30	176	80	98.00
70.00	3.17	8.15	4.35	176	80	168.00
105.00	3.27	8.50	4.55	440	200	273.00
77.00	3.50	8.75	4.75	330	150	350.00
8.5° E 42.5° N—07						
2.00	2.20	2.10	1.20	374	170	2.00
1.00	2.30	3.70	2.15	374	170	3.00
1.50	2.50	3.90	2.25	352	160	4.50
1.50	2.60	4.50	2.60	352	160	6.00
8.00	2.95	5.80	3.35	308	140	14.00
15.00	3.00	7.20	4.25	220	100	29.00
65.00	3.10	8.00	4.40	176	80	94.00
75.00	3.21	8.10	4.35	176	80	169.00
100.00	3.32	8.45	4.65	440	200	269.00
81.00	3.54	8.75	4.75	330	150	350.00
9.5° E 42.5° N—08						
1.50	2.08	2.10	1.20	396	180	1.50
0.50	2.18	2.35	1.35	396	180	2.00
1.00	2.58	4.85	2.80	396	180	3.00
1.00	2.77	5.20	3.00	396	180	4.00
14.00	2.92	6.25	3.60	308	140	18.00
30.00	2.92	8.00	4.30	176	80	48.00
25.00	3.07	8.00	4.40	176	80	73.00
70.00	3.18	8.00	4.30	176	80	143.00
120.00	3.29	8.40	4.45	440	200	263.00
87.00	3.51	8.80	4.75	330	150	350.00

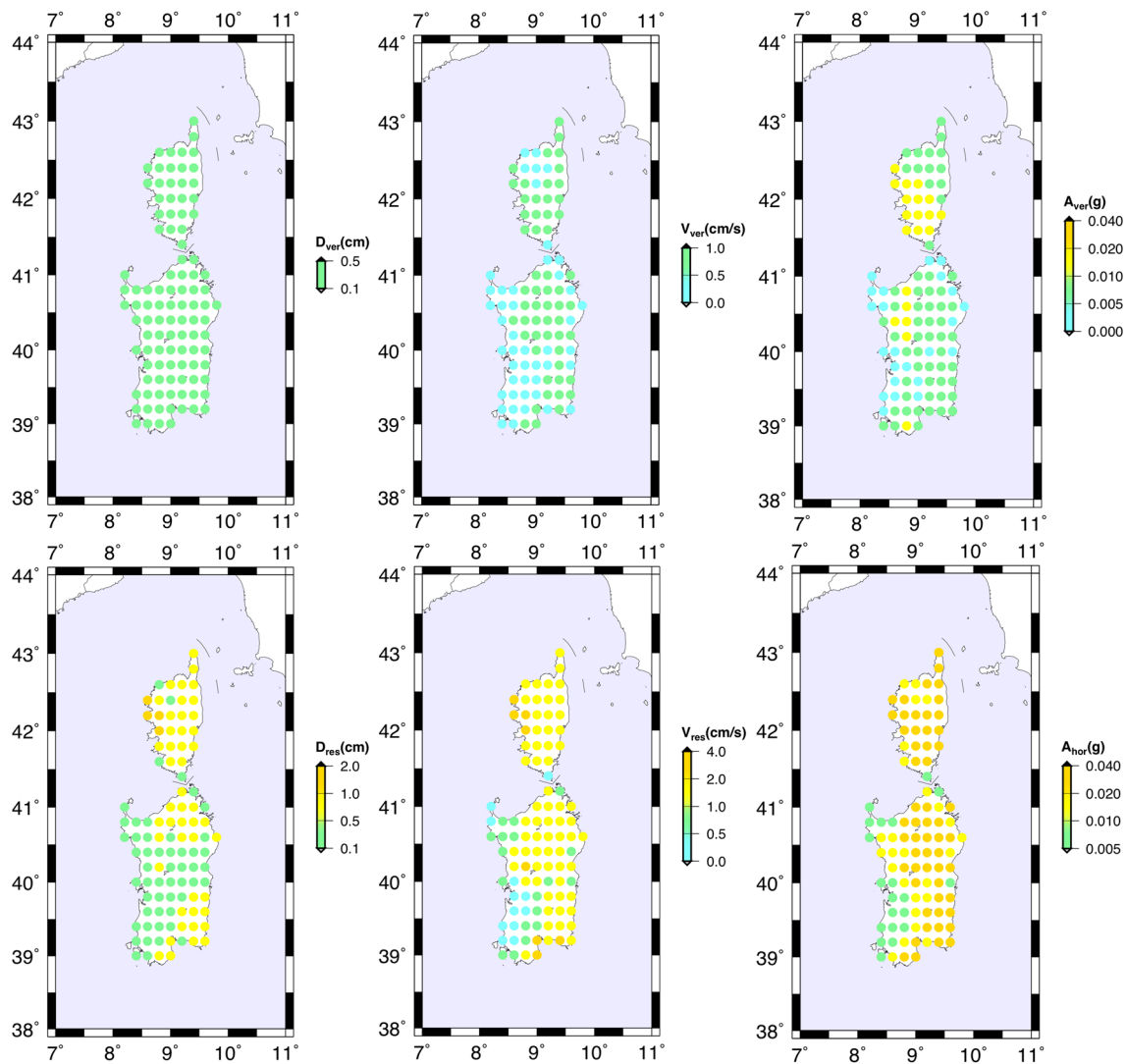
Coordinates refer to the center of  $1^\circ \times 1^\circ$  cells.  $Q_s$  after Martinez et al. (2009, 2010).  $Q_p = 2.2 * Q_s$



**Fig. 4** Hazard maps at 1 Hz cut-off frequency. Top: vertical component; bottom: horizontal component (computed as the resultant of the NS and EW components for displacement and velocity). Acceleration values are obtained using Eurocode 8 (Soil A) to extrapolate

the DGA at  $T=0$  s. Horizontal DGA is evaluated considering either the NS or the EW accelerogram, whichever leads to the highest DGA (color figure online)





**Fig. 5** Hazard maps at 1 Hz cut-off frequency obtained applying  $M_{\text{design}}=5.5$  to the seismogenic nodes (color figure online)

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## Declarations

**Ethical statement** Authors of the manuscript “Neo-deterministic seismic hazard assessment of Corsica-Sardinia block” by Brandmayr E., Vaccari F., Panza, G.F. confirm that the manuscript: Is not submitted to another journal for simultaneous consideration. Is original and has not been published elsewhere in any form or language (partially or in full). Is not a part of a larger study. The manuscript is an independent and completed research. Results are obtained using the objective geophysical and seismological data available to the whole scientific community. No data, text, or theories by others are presented as if they were our own.

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